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ENTROPY IN THE SCHOOL

I.

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of the Roland Eötvös Physical Society

1975 ATOMS IN THE SCHOOL
Proceedings of the First (Vienna) and Second (Visegrád) Danube Seminar on Physics Education

1976 MOMENTUM IN THE SCHOOL
Proceedings of the Third Danube Seminar on Physics Education (Visegrád)

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1981 NUCLEAR PHYSICS - NUCLEAR POWER
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Essay collection about teaching quantum physics in school for the International Committee of Physics Education of IUPAP

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Essay collection about teaching statistical physics in school for the participants of the Sixth Danube Seminar

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Puskin utca 5, Budapest H-1088
(Some copies available in exchange)

GIREP '84

THE MANY FACES OF TEACHING AND LEARNING MECHANICS

in secondary and early tertiary education

CONFERENCE ON PHYSICS EDUCATION
Utrecht - The Netherlands
20-25 August 1984

The 'Groupe International de Recherche sur l'Enseignement de la Physique' (GIREP) will organize its next conference on physics education in 1984 in the Netherlands

The main topic of the conference will be 'the teaching and learning of mechanics in secondary and early tertiary education', including the following sub-topics:

. the use of micro-computers in mechanics teaching
. adaption of mechanics teaching to the world of students;
. research on students' frameworks;
. conteptual analysis of mechanics concepts;
. integration of technological applications of mechanics into physics teaching;
. new ways, experiments and contents in mechanics teaching.

The conference location will be the 'Woudschoten Conference Centre' in Zeist, a small town in the scenic central region of the Netherlands, near the city of Utrecht.

Total cost of attending the conference will be approximately 750 Dutch guilders (300 US Dollars at this moment), including an excursion, welcome party, full accomodation and a special conference dinner.

Those who intend to participate in the conference should inform the local organizers before the end of 1983. In accordance with the general GIREP policy the number of participants is limited, so an early indication of intentions is recommended. Detailed information on the conference will be mailed to interested people at the end of 1983.

Those who are interested in contributing to the conference by a lecture, paper, workshop, poster, exhibition etc. are kindly asked to inform the local organizers by mail as soon as convenient about the kind of contribution, (provisional) title and outline of the contents. Contributions are not limited to the sub-topics listed above; topics outside the list which are also relevant to the teaching and learning of mechanics will be considered as well.

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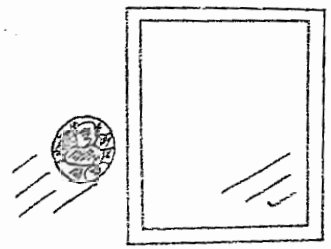
ENTROPY IN THE SCHOOL?

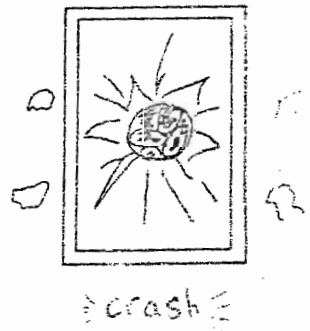
(opening address)

George Marx
vice-president of GIREP

A window broken by a football will not be restored by itself. Each child knows, that most events of the everyday life are irreversible. School, on the other hand, speaks about the two-ways swinging of the mathematical pendulum, about the undamped oscillation of waves. Physics teaching offers the picure of e reversible world, thus loosing a very essential characteristic of reality.

Most school curricula mention the Second Law of thermodynamics as a qualitative remark of small importance. Its quantitative aspects, its logical consequences are considered traditionally to be alienating subjects even at college level, to be certainly too difficult stuff for school instruction. This school practice is in sharp contradiction to the view of contemporary science.





Today science considers the Second Law to be much more relevant than other widely tought physical "laws", like Hooke's law or Ohm's law. It is not just one more empirical relation of physics, but it has turned out to be one of the most essential and universal principles of Nature, unavoidable for the understanding of all the natural science. If we are interested in presenting physics as the foundation of science to our pupils, we cannot afford any longer to restrict ourselves to the reversible scheme of pulleys and alternating currents.

The Second Law holds the supreme position among the laws of Nature - is said by Sir Arthur Eddington. Time depreciates the value of the world - has been written by Horace. Or to quote more recent opinion, that of Peter W. Atkins, a participant of this seminar: The deep structure of change is decay. All these remarks stress the importance of the Second Law to understand Nature, but as we see now, it has a message also for understanding Society. Pollution is an other word for Entropy - can be read in a book Jeremy Rifkin about economy. The title of this best-selling book is ENTROPY. A recent novel by Thomas Pynchon carries the same title and it expresses the ars poetica of the young post-modern generation. Two perils threaten the world: order and disorder - these words of Paul Valery echo already the ideology of contemporary political movements. People start seeing the precondition of progress in the Second Law, both from biological and from social point of view, as if they were rehabilitating the ancient popular Hindu god Shiva, who moves the world by fire and by destruction. As Ilja Prigogine expressed: Mutations and innovations appear always by chance, but they can be incorporated into excisting structures, so they provide for steady evolution.

All of us, even our pupils know from the fairy tale of Cinderella that it was easy to mix ashes with millet seed but it took a lot of effort of fairies or doves to assort them again. (In a more modern version one may mention the easy mixing and hard ordering of Rubik's cube).

Of course everyone knows that the world is made of uncounted many atoms, which get mixed spontaneously, so what is the pedagogical difficulty with the Second Law?

The hard task is to develop the Second Law from a trivial qualitative remark to a predictive quantitative theory, which will have an educational power comparable to that of Newton's laws. Let us not forget, how Newton's dynamics educated generations to exact and causal reasoning!

We all know, what are the options at university.

One may start thermodynamics with Carnot's engine, one gets somehow

$$\Delta S > Q/T$$

by a rather sophisticated logical argumentation. From here it is already easy to get the efficiency of the heat engine. But at the end our students used to ask: "All right, I understand each step, but would you tell me: what is entropy?"

Or, alternatively, one may start with the corpuscular model of the ideal gas. After this motivation one may introduce the entropy S as a logarithm of the number of ways W for possible molecular arrangements:

$$S = k \ln W.$$

Up to this point everything is attractive combinatorics. But now the question arises: how to get from here to

$$\Delta S > Q/T,$$

to practical applications?

If one starts thinking about making the Second Law to a relevant part of school education, the task is to get from the experience of the irreversibely broken glas to the understanding of the roots of pollution and progress,

evolution and creation! Should one start from the apparently simple concept of heat, to obtain somehow $\Delta S \geq Q/T$, then it is easy to explain the heat engines? On this way one may follow a steep path of strict logic or one may dare big jumps. Or should one ask the pupils to throw coins and dice, to catch the idea of disorder and then to write $S = k \ln W$ rather soon? But now to go on? This seminar will search for an answer or - preferably - for different answers to these questions. Each day of the Seminar is devoted to different aspects of teaching about thermodynamics:

The origins of the idea. (The first and the Second Law were discovered, the ideas of energy and entropy were introduced practically silmultaneously together in the 19th centu What is the message of this historical coincidence the schoo practice?)

The psychology of the subject. (Children live in the real world and speak about past and future, strength and wan What is behind their words? Do they understand what school physics means by force, work, heat? At the end of school education can they understand the concept of energy (the ability to perform work or to heat water) better than the concept of entropy (the number of ways, the measure of disorder, the lack of information).

Scientific importance. (Point of view of astronomy, physics chemistry, biology, ecology, economy. Shall we be able to coordinate the efforts of different school subjects in the interest of understanding the arrow of time?)

Approach via the empirical concept of heat. (More direct evidence, more abstract logic, more technical applications.)

Approach via the mathematical concept of disorder. (Disorder has a meaning also for the children's drawer. But the path from here to the invention of the steam engine seems to be a long one.)

School practice. (The gyroscope and the alternating current are at least as sophisticated subjects as the

the applications of the Second Law, but traditional school physics learned how to handle them. If theachers understand the essential ideas, with the help of analogies, models, demonstrations, computers they may solve even hopless tasks.)

In Chinese language the symbol "I can" (ability) is used for energy. The double symbol "fire trade" (or "exchange rate of heat") stands for entropy. There are now teachers and professors among us from several continents, representing disciples. We have got a job from history. Pollution problems and energy crisis have been produced by our generation. It is our duty to explore the pedagogical possibilities for explaining the message of the thermodynamics to the next generation. If they understand the scientific roots of the problem, they may have made half the way toward its solution.

The first talk about the origins of the entropy concept will be given by Prof. Dieter Flamm, the grandson of Ludwig Boltzmann.

The Law of Cinderella

"Fizika" for grade 9, by Buchovcev et a

Moscow

Явление испарения объясняется молекулярно-кинетической теорией. Молекулы жидкости участвуют в хаотическом движении. При этом, чем выше температура жидкости, тем интенсивнее движутся молекулы, тем больше их кинетическая энергия. Но только среднее значение кинетической энергии молекулы имеет при заданной температуре определенную величину. У каждой молекулы энергия в данный момент может оказаться или меньше, так и больше средней. Кинетическая энергия некоторых молекул может оказаться столь большой, что они способны вылететь из жидкости, преодолев силы притяжения остальных молекул. В этом и состоит процесс испарения (рис. 51).

Рис. 52

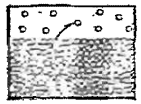
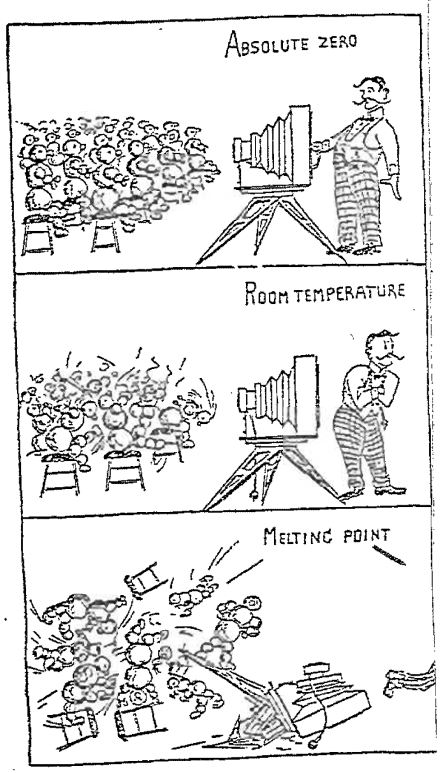


Рис. 53

PLON "Energie en Kwaliteit", Utrecht



ORIGINS

IT DOES NO GOOD TO CRY OVER THE SPILT MILK.

American proverb

TIME DEPRECIATES THE VALUE OF THE WORLD.

Horace

ENTROPY IS TIME'S ARROW.

Sir Athur Eddington

EXPANSION MEANS COMPLEXITY AND COMPLEXITY MEANS DECAY.

Parkinson's Third Law

THE DEEP STRUCTURE OF CHANGE IS DECAY.

Peter Atkins

POLLUTION IS AN OTHER WORD FOR ENTROPY.

Jeremy Rifkin

TWO PERILS THREATEN THE WORLD: ORDER AND DISORDER.

Paul Valery

FOR A HEAT ENGINE OPERATING IN CYCLES TO PERFORM MECHANICAL WORK WE MUST USE TWO BODIES OF DIFFERENT TEMPERATURE.

Sadi Carnot

ONCE OR TWICE I HAVE ASKED GATHERINGS OF PEOPLE WHO - BY THE STANDARDS OF TRADITIONARY CULTURE - ARE THOUGHT TO BE HIGHLY EDUCATED: HOW MANY OF THEM COULD DESCRIBE THE SECOND LAW OF THERMODYNAMICS. THE RESPONSE WAS COLD: IT WAS NEGATIV. YET I WAS ASKING SOMETHING WHICH IS ABOUT THE EQUIVALENT OF: HAVE YOU READ A WORK OF SHAKESPEARE?

C.P.Snow

THE H-THEOREM AND BOLTZMANN'S PRINCIPLE FROM THEIR ORIGINS UNTIL TODAY

Dieter Flamm
Institut für Theoretische Physik der Universitat Wien

1. The Criticism

Right at the beginning I want to stress that I shall take up the gauntlet of Boltzmann's case and as a grandson of Boltzmann I shall defend his ideas against criticism. It is remarkable that 111 years after Boltzmann's fundamental paper on the H-Theorem [1,2] where he gave a functional H[f] of the molecular distribution function f which always decreases with time doubts concerning this theorem are still raised [3]. More deplorable are, however, the unfounded suppositions regarding Boltzmann's personality. In the April issue of Physics Today [4] one finds a picture+ of Boltzmann's grave under the headline "A physicist left behind by the twentieth century." Quite on the contrary Boltzmann paved the way for the great theories of the 20th century namely for the theory of relativity and for quantum mechanics and always had an open mind for new developments. The latest information proving this statement can be found in the Proceedings of the International Conference commemorating the 75th anniversary of Boltzmann's death [5]. Boltzmann's statistical interpretation of the second law in 1877 [6,7] is summarized by the equation

$$S = k \ln W \qquad (1)$$

where S is the entropy, k Boltzmann's constant and W the thermodynamic probability or the number of complexions of a given macrostate. Initially not even M. Planck who later became one of the main promotors of Boltzmann's ideas [8,9] accepted Boltzmann's statistical interpretation of the second law which has been called Boltzmann's principle by A. Einstein. Also this statistical interpretation has been attacked in a widespread book [10]++. Quite recently I obtained a long distance call by an American scientist, who claimed that he had just discovered a mistake in Boltzmann's 1877 paper and wanted to know whether this error was the reason for Boltzmann's suicide. We physicists know of course that Boltzmann's paper is

+) Furthermore in the figure caption it is erroneously claimed that the chapel in the background of the picture is the University of Vienna while it really is the Lueger chapel on the central graveyard of Vienna.

correct. Under the heavy attacks of his opponents, however, Boltzmann himself had sometimes doubts on the validity of the H-theorem[+++].

Even the founder of Synergetics [11] has expressed his surprise in a recent talk in Vienna [12] that Boltzmann, a great admirer of Darwin, did not realize that biological evolution and the second law of thermodynamics were incompatible. There is, however, no contradiction between the second law which applies to closed systems and the evolution of dissipative structures which are always open systems with internal friction [13]. In certain very limited domains of the dynamical variables of a dissipative system far off from the thermodynamic equilibrium the dynamical fluctuations postulated by Boltzmann [14] in his Presidential Address to the British Association at Oxford in 1895 may be enhanced and locally lead to the emergence of ordered structures [8].

At Boltzmann's lifetime the physical chemist W. Ostwald was Boltzmann's main opponent. Also today Boltzmann's ideas that the fundamental time-reversible invariant microscopic laws are under certain limiting conditions compatible with the irreversible behaviour observed in the nature are citisized by a Nobel laureate in chemistry, namely I. Prigogine who writes [3]:

"Regardless of different statements one cannot consider Boltzmann's H-theorem as derived from the dynamics , and in this point we agree with statements by Poincaré. Boltzmann's kinetic equation, on which the derivation of the H-theorem is based, does not have the symmetry of classical dynamics. In spite of its historic importance it is at most to be considered as a phenomenological model."

Mainly on philosophical grounds Prigogine wants irreversible phenomena to be more fundamental than just phenomena which emerge using the time-reversible invariant dynamics, certain randomness assumptions on the initial conditions and an averaging and a limiting procedure. As Boltzmann

++) This book is apparently written for economists and politicians and contains numerous mistakes as far as physics is concerned.

+++) Compare a letter of Boltzmann to F. Klein, K. Meyenn, Boltzmann als Kritiker und Rezensent, in: Ausgewählte Abhandlungen der internationalen Tagung, Wien 1981, Vieweg 1982, ref. 5, p. 121.

stresses in his reply to Zermelo Poincaré's recurrence argument does not apply if the number of particles goes to infinity [15]: "If one let first the number of gas molecules go to infinity, as it is done in the proof given in my Theory of Gases in § 5, and only afterwards let the time of the motion become very large ... Poincaré's lemma is not applicable." In the same way the recurrence paradox does not hold for any system with an infinite number of degrees of freedom, as for instance modern quantum field theory. In fact outgoing spherical waves are a phenomenon which one easily observes in every day life while incoming waves which converge to a point are very hard to prepare.

2. Is Irreversibility Just an Approximation?

In response to Prigogine's statement we must admit that Boltzmann's kinetic equation is not time reversal invariant, but it must also be stressed that it has been derived from classical dynamics by Lanford [16] using the so-called Grad limit. Furthermore the quantum mechanical generalization of the Boltzmann equation for a Fermi-gas has recently been derived by Hugenholtz [17]. Hugenholtz starts his paper with the remark:

"Hardly any equation in theoretical physics has evoked as much discussion and controversy as the Boltzmann equation. Much of the discussion was and still is centered around the fundamental question at what point and through what assumption irreversibility in time was introduced. In the original derivation by Boltzmann an essential feature is the Stoszzahlansatz, an assumption about the lack of correlation between the velocities of two colliding particles. This assumption must be made not only at the initial time, but at all times."

The derivation of kinetic equations such as the Boltzmann equation from reversible dynamics always contains an averaging and a limiting procedure. With these procedures one can show that if the randomness assumption on the initial condition is made at one time it will hold for all times. One cannot obtain the Boltzmann equation from reversible

dynamics by merely performing the so-called "thermodynamic limit". This limit consists in letting the particle number n and the volume V go to infinity while n/V remains finite. One needs additional assumptions such as the Grad limit where not only the number of molecules goes to infinity but at the same time the size of the molecules or equivalently their scattering cross section shrinks in such a way that the mean free path of the molecules between two-body collisions remains constant. By this limiting procedure Boltzmann's Stoszzahlansatz emerges in a natural way [16].

Besides the Grad limit one can apply different limiting procedures such as the mean field limit, the weak coupling limit, the hydrodynamic limit etc. One may even start from the very same Hamiltonian or Hamilton-operator and obtain different kinetic equations depending on which limiting procedure has been applied. A good review of this subject is given in the article by H. Spohn [18] "Kinetic equations from Hamiltonian dynamics: Markovian limits". To Prigogine the need for such limiting procedures appears unesthetic. In practice all the systems we consider are finite. One can calculate Boltzmann's H-functional

$$H[f] = \int_V d^3x \int_{-\infty}^{\infty} d^3v \; f(\vec{x},\vec{v},t) \log f(\vec{x},\vec{v},t) \qquad (2)$$

where $f(\vec{x},\vec{v},t)$ is the space and velocity distribution of a typical molecule, which implies averaging over all molecules except one for a finite system. If one actually calculates H[f] on a computer for a two-dimensional distribution of elastic disks in a plane for rather small numbers of elastic disks (n = 100, 484, and 1225) one obtains the H-curves shown in Fig. 1 [19]. Here the starting point corresponds to a distribution function $f(\vec{x},\vec{v},0)$ at t = 0 where all disks occupy lattice points in a plane but have random velocities. If in addition one reverses all velocities of the disks after 50 or 100 collisions, respectively, which corresponds to a time reversal and introduces correlations between the disk-velocities which make the H-theorem unvalid for a certain period of time, one obtains the H-curves in Fig. 2 [19]. Thus even for n = 100 the time evolution of the disks obeys the H-theorem rather well. If all velocities are reversed

after 50 or 100 collisions, respectively, it takes the system very little time until it forgets these correlations and returns again closely to the equilibrium value. For a small volume of dilute gas this recovery time is of the order of microseconds. Already after a few collisions the correlations are wiped out again. Similarly if one calculates the Poincaré recurrence time one obtains [20] $t_R \sim e^n\big|_{n=100} \sim 3 \cdot 10^{43}$ seconds. This means that until the disks all simultaneously return again close to regular lattice sites in the average a time which is by many orders of magnitude larger than the age of the universe which is only 10^{17} seconds has to pass. Thus for all practical purposes Boltzmann's statistical approach works already for rather small particle numbers such as n = 100. Only for a rigorous mathematical proof of the emergence of irreversible behaviour from time-reversal invariant dynamics one has to invoke limiting procedures with $n \to \infty$ and other assumptions. In other words Boltzmann's arguments work already for a finite number of particles. But for a finite system with a finite number of particles the irreversible behaviour is not absolutely certain as in the limiting case but it is extremely probable.

3. The Akward Behaviour of Physical Systems

Only for a very limited class of physical systems for the so-called integrable systems such as the harmonic oscillator, the Kepler-problem etc., the solution of the equations of motion can be written down in closed form. All these systems have a very simple structure. It can be shown that they can be decomposed into subsystems with only one space- and one canonically conjugate momentum variable. The solutions of all other systems cannot be given in closed form. Their time evolution may have bifurcation points where the system passes through singular points (compare Fig. 3). The bifurcation point is a branch point of the trajectory of the system which corresponds to a critical value λ_c of some parameter λ of the system. At the bifurcation point an element of chance is introduced: the system may follow either one or the other branch of the evolu-

tionary trajectory. Many such once for ever decisions have been taken during the biological evolution of life. A further undeterministic element for the long range evolution of complex systems of many particles is the so-called weak stability. In terms of classical trajectories weak stability means that trajectories which start from neighbouring points in phase space will go in entirely different directions of phase space (compare Fig. 4) [3]. Since we cannot know the initial conditions of the system with 100 per cent accuracy the future of the system is again only statistically determined. This means various final states may occur due to the error in our knowledge of the initial conditions. Thus we have to give up the deterministic point of view and we have to be satisfied even classically with statistical predictions for complex systems. In quantum mechanics one says correspondingly the system shows strong mixing properties. For a large system the number of states Z with a given energy E grows exponentially with the number of particles n

$$Z(E) \propto e^{n} . \qquad (3)$$

Thus for a large enough number of particles n = 100 or 1000 the energy levels will be so dense that any small perturbation will cause mixing of the states of the system. Different states have, however, a different time evolution.

As stated in the last paragraph different domains of the dynamical variables may imply quite different kinetic equations. Different kinetic equations may give an adequate phenomenological description of one and the same Hamiltonian system in different domains of the parameters of the system. A class of linear equations of this kind for the density operator $\rho(t)$ which have the general form [21,22]

$$i\hbar \frac{d\rho(t)}{dt} = [H,\rho] + \text{dissipative terms} \qquad (4)$$

can be derived for subsystems of a large system. One calls these equations "master equations". The dissipative terms correspond to energy changes due to friction and/or radiation.

The more interesting behaviour arises if the kinetic equation of the system is a nonlinear equation of the form

$$\frac{d}{dt} x(t) = F_{\lambda}(x(t)) , \qquad x(0) = y , \qquad (5)$$

where F_{λ} is a nonlinear function of the variable x which depends on a parameter λ. λ may be the strength of a driving force, the amount of friction, or the amount of chemicals added per time unit, etc. Such a system may exhibit so-called "attractors", loosely speaking metastable states, which the system approaches. A detailed account of some possible scenarios for such systems is given by J.P. Eckmann "Roads to turbulence in dissipative dynamical systems" [23].

I have no time to go into details and therefore I shall only demonstrate to you certain possible scenarios using two examples.

A very simple dissipative system which I shall use to demonstrate the change in the kinetic behaviour of dissipative systems is the magnetic pendulum+. As most other dissipative systems it shows a quite different behaviour, depending on what its mechanical energy is. It is essentially a mathematical pendulum disturbed by the potential barriers of the magnets. For large amplitudes it shows a simple nearly periodic motion. For amplitudes comparable with the distance of the four magnets from the center, it develops a chaotic random walk behaviour. Finally for very small energies it performs again a nearly harmonic motion around a minimum of the potential energy. This simple example is well known from the theory of small oscillations around a stable equilibrium state.

Another simple example is the following. If you take a worn out g-recorder and blow very gently you will hear only the g'. If you blow stronger g' and g" will be audible. If you blow jet a little stronger even three frequencies may be heard. Finally if you blow very strong you will just hear plain noise which corresponds to turbulence. The interesting thin which also happens in many other systems is that in a limited range of the parameters one mode will absorb all the energy. In this case the system corresponds to an ordered structure. The turbulence on the

+) One can buy it in various stores under the name "gyration" and demonstrate its motion to a large audience on an overhead projector.

other hand corresponds to chaos.

4. Apparently Irreversible Behaviour

A well known difficulty in the derivation of irreversibility is the fact that the usual classical expression for the entropy in terms of the density of states in the 6n-dimensional phase space $\rho(p_k,q_k)$ (k = 1,2,..3n) [21]

$$S^{cl} = - k \int \frac{d^{3n}p\, d^{3n}q}{h^{3n}} \rho^{cl} \ln \rho^{cl} \qquad (6)$$

for a closed system is constant if ρ obeys Liouville's equation. Just the same thing happens in the quantum mechanical case [21]

$$S = - k \, Tr \, \rho \ln \rho \qquad (7)$$

where ρ is the density operator. A remedy for this puzzle in the classical case has been given by P. and T. Ehrenfest in 1911 who proposed to consider instead of ρ^{cl} the coarse-grained density in phase space $\bar{\rho}^{cl}$ [24]. $\bar{\rho}^{cl}$ is averaged over a small neighbourhood of each point since macroscopic observation is, by its nature, unable to determine actual points in phase space. The entropy obtained from $\bar{\rho}^{cl}$ is not constant but increases with time. Boltzmann's quantity H in eq. (1) contains an even more radical averaging procedure, which is averaging over all particle positions and momenta except one ($\vec{x} = \vec{q}_1$, $\vec{v} = \vec{p}_1/m$) [21]

$$f(\vec{x},\vec{v},t) \propto \int \frac{d^3p_2 d^3q_2 \ldots d^3p_n d^3q_n}{h^{3n}(n-1)!} \rho^{cl}(\vec{p},\vec{q},\vec{p}_2,\vec{q}_2 \ldots t) \; . \qquad (8)$$

It is tempting to ask whether there are any systems in nature which show naturally an increase in entropy without any coarse graining. The simplest example is a Gaussian wave packet corresponding to a particle at rest at $\langle x \rangle = 0$

$$\psi(x,0) = (2\pi)^{-1/4} \, a^{-1/2} \, e^{-x^2/4a^2} \; . \qquad (9)$$

The width of such a wave packet increases linearly with time

$$\Delta x = \sqrt{\langle x^2 \rangle - \langle x \rangle^2} = a \sqrt{1 + t^2/\tau^2} \qquad (10)$$

with $\tau = 2ma^2/\hbar$ where m is the mass of the particle. Of course, eq. (10) is still time-reversal invariant because it depends only on t^2 yet the inaccuracy of the position of a free particle increases with time.

A more sophisticated example is a gas of free Fermi particles which at time t = 0 is contained in the volume V. With increasing time this gas of Fermi particles will spread out further and further into space. From the expectation value of the density matrix $\rho(x) = \langle x|\rho|x\rangle$ one can form an expression for the entropy similar to eq. (7) and finds that it increases with time [22]. Of course, also in this case one could imagine the inverse, namely a Fermi gas converging into the volume V, however, this situation is extremely unlikely. One could use the expanding Fermi gas as a very simplified model of the expanding universe. One could even speculate what would happen if one switches on gravitation and the system becomes a Friedman universe. In this case the Fermi gas will recontract after reaching its maximal extension. Yet when it recontracts the entropy of the whole system will not decrease because the system will emit gravitational- and if the particles are charged also electromagnetic radiation. The transformation of kinetic energy into radiation amounts to a large increase in the entropy density. Thus such a system will certainly not return to its original state. The emission of radiation which is not included in a purely mechanical consideration seems to be one of the main sources of entropy increase. The emission of one photon of black body radiation corresponds to an entropy increase of 5.19 bit [8]. A large part of the entropy density of our universe is accounted for by the 2.7°K black body radiation [25].

In the last decade physicists have made great progress in understanding the microscopic laws of nature. Nowadays we believe that quarks, leptons, gluons, the photon and the heavy vector bosons of the weak inter-

actions which are unified by the Grand Unified Gauge Theory are the fundamental constituents of matter [25]. This theoretical framework allows not only to understand elementary particle spectroscopy but also the gross features of the evolution of the whole universe. In the beginning there was perfect symmetry which only afterwards became spontaneously broken as the universe was expanding. From an elementary particle physicist's point of view there seems no need to abandon Boltzmann's unifying concept and to introduce an entropy operator which obeys canonical commutation relations with a fictitious time operator [3].

References:

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The author would like to thank Dr. A. Pflug for suggesting the magnetic pendulum and the g-recorder as demonstration objects. All members of the Theoretical Physics Institute in Vienna he wants to thank for valuable discussions. Last but not least he would like to thank Professor G. Marx for the pleasant atmosphere at the Danube Seminar on Physics Education in Balatongyörok.

Figure captions

Fig. 1 The time evolution of Boltzmann's H[f] calculated on a computer for a system containing a total number of (a) n = 100, (b) n = 484, and (c) n = 1225 discs. The starting point corresponds to a distribution where the discs occupy lattice points in a plane and have a random velocity distribution. After about n collisions a random space distribution is reached.

Fig. 2 The evolution of H[f] as in Fig. 1 for n = 100 if the velocity of all discs is reversed after 0, 50, or 100 collisions, respectively. The random distribution at the beginning remains random even if all velocities are reversed. A reversal after 50 or 100 collisions violates, however, the randomness assumption of the H-theorem for the distribution and introduces correlations between the velocities. The discs are now forced to repeat the 50 or 100 collisions undergone since t = 0 backwards in reversed order. Correspondingly H[f] rises and the discs return to their initial lattice points. After 2n collisions every trace of the correlations has disappeared again.

Fig. 3 Complex physical systems may show the bifurcation phenomenon. As the solution reaches the critical value λ_c of the parameter λ, it has the option to choose one of the two branches as λ increases further.

Fig. 4 Weak stability means that the trajectories of neighbouring points in phase space go in different directions. While the volume in phase space as a whole remains constant it is chopped up into many little pieces which are spread out over a large region in phase space. (Compare also ref. 22).

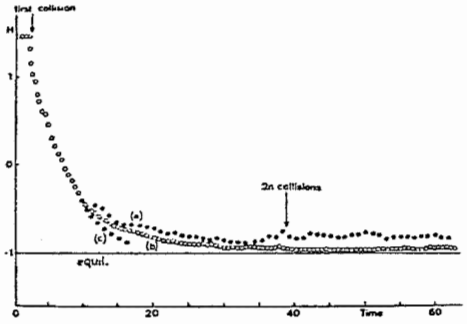


Fig. 1

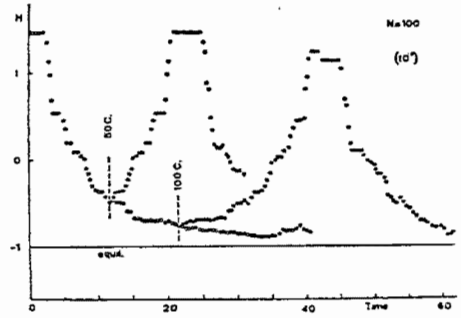


Fig. 2

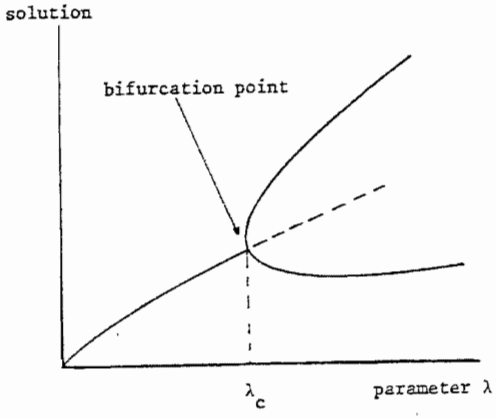


Fig. 3

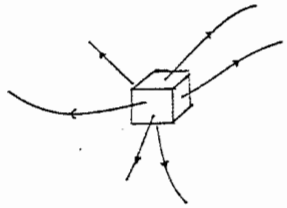
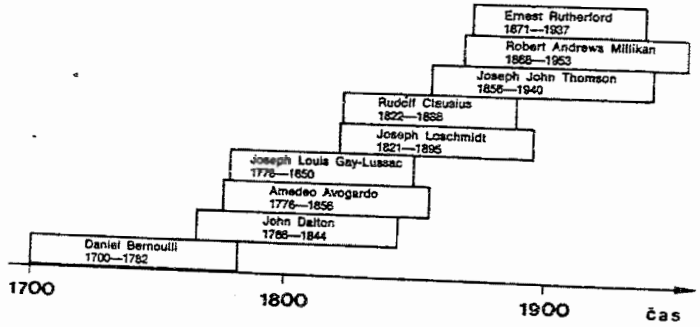
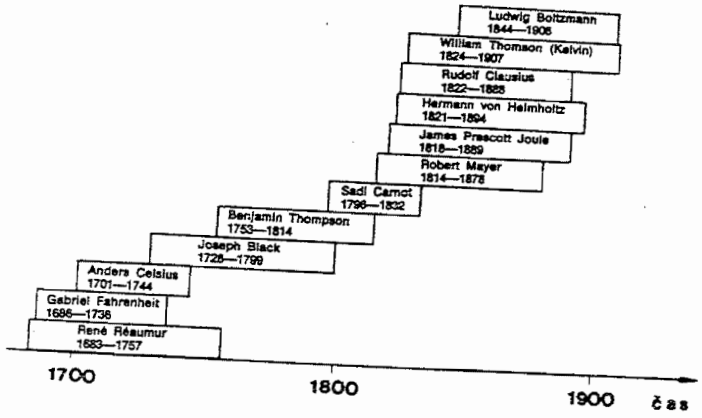


Fig. 4





from "Fizika za druzboslovno usmeritev" for grade 10
by Janez Strnad, Ljubljana

HOW CLAUSIUS INTRODUCED THE CONCEPT OF ENTROPY

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In 1872, the fifty-year-old Rudolf Clausius /professor at the University of Bonn/ was elected honorary member of the Hungarian Academy of Sciences, in company with Helmholtz and Kirchhoff. This was a really extraordinary event at the time as more than 10 years had passed since a foreign physicist had been elected to the Hungarian Academy. /The first one - in 1847 - was Pncelet, who introduced the exact meaning of mechanical work, in 1829./

In 1872, Rudolf Clausius was the greatest authority on thermodynamics. Seven years earlier, he had introduced a new physical quantity - called by himself the "entropy"- in order to make more clear the meaning of the Second Law of Thermodynamics.

To understand his ideas, to appreciate his intellectual achievements, we have to remember the circumstances. In 1844, Clausius was 22 years old, and he had just finished his studies at the University of Berlin. In those years, the theory of caloric was just about collapsing. It became necessary to revise the ideas about heat. What kind of ideas did exist then?

The naiv materialistic view of Nature, the extension of which was helped by the enlightenment at the end of the XIIIth century, suggested that in every class of phenomena there must exist a characteristic substance - like quantity which remains unchanged in natural processes. In this way the mass became the quantity of matter that is conserved in chemical reactions. Thus was introduced the charge Q in electric processes, as the conserved quantity of electricity. And in a similar way, Black, succeeded in distinguishing the temperature and the heat quantity Q, and gave instructions for the measurement of this quantity in 1760.

The experiments, carried out by Joule, in the forties of the last century, had proved not only the non-conservativity of the heat quantity Q, but had demonstrated the existance of a "mechanical equivalence" too, which could be expressed in terms of mechanical work. Joule, who was thinking in a practical way, was not at all surprised that a quantity - believed conserved - had disappeared from physics. All the more did this fact embarrass the philosophically more educated Mayer and Helmholtz, who had a strong belief in the conservation of some sort of general cause or power which must have a physical equivalence.

For Clausius, it was not a serious problem to reconcile the different views of Helmholtz and Joule, declaring

the First Law of Thermodynamics:

"...from the equivalence theorem of vis viva and work, it is possible to deduce the First Law of Thermodynamics, which we shall call the equivalence of heat and work."

The expression "equivalence" was introduced by Joule while the extension of the theorem of vis viva was the idea of Helmholtz.

From the statement of the First Law it is obvious that Clausius had an excellent talent to reconcile the different views. And really, it was his systematical mind, that led him to the statement of the Second Law.

The exact meaning of mechanical work had not yet been clearly established, when Carnot published a work in 1824: "On the promoting power of fire..."./"Reflexions sur la puissance notrice du feu"/ In this work he investigated the amount of mechanical work that can be done by heat engines.

In his paper, Carnot tried to answer the most urgent question of that time: whether there was anything, limiting in principle the maximum efficiency that could be achieved by heat engines.

His fundamental idea was that in heat engines working between different temperatures the heat is transferred from a place at a higher temperature to a place at a lower temperature. As the water - falling down from a higher place to a lower one - can do some work, so heat can do it too flowing from the place at a higher temperature to a lower one. And he led this analogy much further supposing that as the quantity of water falling down remains unchanged, so the heat quantity remains also unchanged while it works. In more general terms, we can say now that - according to Carnot's idea - the heat quantity flows from one place to another in a similar way as a charge moves between places of different potentials in a conservative field.

The statement of the First Law of Thermodynamics had put Carnot's idea in a strange light: it was discovered that this idea was fundamentally wrong. What was to be done?

Was it inevitable to step over this theory like an idea untenable and out-of-date, or was there any way to save it? There were at least two reasons to maintain it. First, this idea arose from real practical requirements, and secondly: Carnot's theory was the basis of a universal theoretical temperature scale of fundamental importance, established by Thomson in 1848. This temperature scale was based upon the measurement of efficiency - that is: on the measurement of heat and work. But - according to Carnot - heat can do some work and from the experiments of Joule it was clear that work can be converted into heat too. /The French Academy has refused plans of "perpetuum mobiles" since 1775!/ And undoubtedly: the impossibility of constructing a "perpetuum mobile" was a fundamental point in Carnot's reasoning, too!

To solve this apparently antagonistic contradiction and to reconcile the opposite views, was a problem that fitted Clausius well. /It is not unimportant that Clausius had grown up in a family of 18 children: he was the sixth. In such a large family it could have been an everyday problem to settle disagreements./ In 1850 - this was the last year when Clausius worked as a teacher in a grammar school - he published this solution as follows: There are two independent fundamental laws in thermodynamics, which are not in contradiction with each other, but they give answer to different questions.

Clausius considered Joule's result declaring that heat always has a mechanical equivalent as a peculiar equivalence theorem. He said that: "in every case when work is done by heat, there is an amount of heat apparently disappearing, which is exactly proportional to the work done", and he considered the equivalence of heat and work as the First Law of Thermodynamics. If in a "simple" cycle /as Clausius calls the Carnot-cycle/ the medium used for working absorbs heat Q_1 at a temperature T_1, and rejects heat Q_2 at a temperature T_2, then the work done by it is equivalent to the difference of heats: $Q_1 - Q_2$.

Carnot's idea, namely that the heat quantity remains unchanged in a transition from a temperature T_1 to a temperature T_2, can be saved if we take into account only the heat quantity Q_2. It was Clausius' brilliant idea that in a cycle there are two different changes that may happen simultaneously: The transformation of heat into work, and the transformation of heat into heat. In a reversible cycle the two kinds of transformations are "equivalent". In his further publications, Clausius could show the way how to calculate the equivalents of transformations "from heat into work", and "from heat into heat". In the case of simple, reversible Carnot-cycles:

$$\underbrace{-\frac{Q_1 - Q_2}{T_1}}_{\text{from heat into work}} + \underbrace{Q_2\left(\frac{1}{T_2} - \frac{1}{T_1}\right)}_{\text{from heat into heat}} = 0$$

One can see that the "equivalent" of transformation is positive in one case and negative in the other one. The equivalence itself is defined by Clausius in such a way that in reversible cycles the two kinds of transformation just compensate each other.

Clausius makes clear distinctions between positive and negative transformations and processes. For example, he considers the transformation of work into heat positive in case of friction, or when heat is transferred from a hot body to a colder one. The process is negative when heat is transferred into work, or in case of heat-transfer from a cold body to a warmer one. And while a positive process can be carried out by itself; negative process may occure only if simultaneously there are positive processes to compensate them.

The Second Law of Thermodynamics - as it has been formulated by Clausius - is the following: "It is impossible to transfer heat from a cold body to a warmer one without any compensation."

Restricting himself to reversible cycles, Clausius was able to state the Second Law of Thermodynamics in the form of an equivalence theorem. And from this equivalence theorem there exist a direct logical way leading to the concept of entropy. The main steps of this deduction are the following:

For a simple Carnot-cycle:

$$-\frac{Q_1 - Q_2}{T_1} + Q_2\left(\frac{1}{T_2} - \frac{1}{T_1}\right) = 0$$

Reducing this equation we get:

$$\frac{Q_1}{T_1} - \frac{Q_2}{T_2} = 0$$

If we prescribe sign for heat quantities in such a way, that heat rejected by the body used in the cycle /that is the heat absorbed by reservoirs / is positive, then $Q_1 < 0$, $Q_2 > 0$, thus:

$$-\frac{Q_1}{T_1} - \frac{Q_2}{T_2} = 0$$

For simple cycles, including infinitesimal isothermals:

$$-\frac{dQ_1}{T_1} - \frac{dQ_2}{T_2} = 0$$

Now, an arbitrary reversible cycle can be split into infinitesimal reversible simple cycles and after summarising, we get:

$$-\int \frac{dQ}{T} = 0$$

Clausius wrote down this equation in 1854. But only after more than 10 years, in 1865, did he introduced the transformation-function S, defined by:

$$\frac{dQ_{rev.}}{T} = dS$$

He called this quantity "entropy". /The original Greek word τροπη means transformations, transmutations, Clausius created from this word the name "entropy". This Greek expression is the cammon root of several nouns used nowadays. For example: "isotropic" means that something remains unchanged in all directions. "Tropics" means the temperate zone separating the northern part of the globe from the southern one. A "tropic year" means the year referred to solictices. "Tropism" is the property of plants to turn in a definite direction, e.g. "phototropism", "geotropism", etc. In music "tropics" means ornamental turns in melodies of Gregorian songs./

Further on Clausius came to the conclusion that the expression :

$$N = -\int \frac{dQ}{T}$$

may be positive only in case of an irreversible cycle. He recognised very clearly that either of the two principal laws of Thermodynamics provides a definition for a different thermodynamical property of the body. He also knew, that neither heat, nor work were thermodynamical properties.

He interpreted the concept of internal energy for gases, on a "molecular" scale: but he did not give any molecular interpretation of the concept of entropy.

He emphasized that entropy is a characteristic property of the body, but he interpreted the entropy-change as the transformational-equivalent of reversible heat transfer. In his calculations heat had a temperature, and the entropy--change was the transformational equivalent of heat.

So, it is not surprising that the microscopic interpretation of entropy had arisen only after a long and exhausting work of the most brillant brains.

The intellectual achievement of Clausius was a chal-

lenge to young talents for decades. Only two examples:

In 1886, one year after the introduction of the entropy concept, the 22 year old Boltzmann chose the deduction of the Second Law from mechanical principles, as his PhD thesis.

In 1879, three years after the publication of Clausius collected works, the 21 year old Planck in his PhD work made a rigorous critical analysis of the Second Law of Clausius..

And now, what does the knowledge of the entropy concept of Clausius mean to present-day teachers?

First, it helps to understand the connection between entropy and the original root of this word.

Secondly, it is perhaps exciting to become acquainted whith the synthetic and creative methods of Clausius.

It may also arouse interest in the researches of Boltzmann, Planck or Szily Kálmán, Clausius' theory triggered their researches.

Finally, I wish that this example would increase the self-confidence and creativity of teachers, as the man who developed these ideas was a teacher, too.

Though, more than 130 years ago...

THAT WHICH BURNS NEVER RETURNS.

A slogan seen on the vans of fire appliance company, quoted by Nuffield A - 9.

A QUASI-HISTORIC WAY TO ENTROPY

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In the time of energy shortage it is of primary importance to teach the second law of thermodynamics to the entire population in secondary school. At present, approaches to the second law based on the microscopic picture connecting entropy with missing information and disorder, are favoured. However, the older phenomenological approach may show its advantages in a particular educational situation. Let us briefly describe a proposal of this kind.

Initially, it is stressed that there is a variety of phenomena which, though allowed by the first law, are not observed in nature. On the way towards a more restrictive law reversible and irreversible processes are discussed at some length. Introducing cycles it was realized that according to the first law a system can reject work $-W$ if it absorbs the same amount of heat Q or reject heat $-Q$ if it absorbs the same amount of work W. Restricting ourselves to periodically operating engines the concept of the ideal engine is introduced. This engine repeats a reversibly cycle and absorbs heat at higher temperature T_2 only and rejects it at lower temperature T_1 only. For an amount absorbed it gives off the maximum work.

Experiments show that this work is proportional to the temperature difference $T_2 - T_1$. Thus, work cannot be given off on the account of absorbed heat only: an isothermal engine, i.e. perpetual motion of the second kind,is not viable. For experimental demonstration one can use, in

general,

i hot air (Stirling) engines [1], as purchased by, e.g. Heraeus-Leybold,

ii bateries of thermocouples with a miniature motor, as purchased by, e.g. Griffin & George,

iii thermal contraction and expansion engines: rubber band engines [2], steel [3] and plaster of Paris engines etc.

The last give qualitative results only, since heat is absorbed and ejected at temperatures below T_2 and above T_1, respectively, while the first two can give quantitative results. If the torque of friction can be taken as constant it is sufficient to show that the frequency of the engine is proportional to $T_2 - T_1$. Otherwise the external torque must be measured at constant frequency using a Prony brake and the power computed; a linear dependence on $T_2 - T_1$ is expected for sufficiently hygh temperature differences.

The experimentally verified equation

$$-W = \text{const.}(T_2 - T_1) \qquad (1)$$

is compared with the result of the first law for a cycle

$$-W = Q_{net} = Q_2 + Q_1 \qquad (2)$$

in which $Q_2 > 0$ is the absorbed heat at T_2 and $Q_1 < 0$ the rejected heat at T_1. Both equations can be made to agree if we demand proportionality of heat with temperature:

$$Q_2 = T_2 \Delta S_2 \qquad Q_1 = T_1 \Delta S_1 \qquad (3)$$

The coefficient of proportionality has been given the form of a difference $\Delta S_2 = -\Delta S_1$. The corresponding quantity - the entropy S - is namely a thermodynamic quantity since its net change in a cycle is zero: $\Delta S_{net} = \Delta S_2 + \Delta S_1 = 0$. Thus, for a general reversible isothermal process

$$\Delta S = Q/T \qquad \text{reversible} \qquad (4a)$$

As for an irreversible engine the work given off is less than for the corresponding reversible one, it follows finally that for a general irreversible isothermal process

$$\Delta S > Q/T \qquad \text{irreversible} \qquad (4b)$$

Hence, according to (4) systems exchange entropy exchanging heat, similarly as they exchange energy. In reversible processes entropy, as energy, is conserved, however, in irreversible processes entropy is produced. For a thermally isolated system namely (4a) and (4b) give

$\Delta S = 0$ reversible (5a) $\Delta S > 0$ irreversible (5b)

Once produced, one cannot get rid of the entropy in an isolated system. If parts of an isolated system are initially not in thermal equilibrium the entropy of the system is increasing till it does not reach the maximum in equilibrium.

So far the equations are valid for any system. Later on processes with an ideal gas are studied. The change of entropy for reversible isothermal expansion of mass m and molecular mass M is calculated: $\Delta S = (m/M)R\ln(V_2/V_1)$. Equations (1) and (3) are verified for a reversible cycle consisting of two isothermal and two adiabatic processes. As an example of an irreversible process free expansion is considered. Initially the gas is contained in volume V_1, then the separating wall is removed and it expands into vacuum, the total volume being now V_2. The change of entropy is thereby the same as for the corresponding isothermal expansion.

Finally, the background of the second law is discussed on a microscopic scale for an ideal gas, i.e. for independent

molecules. It is V_2/V_1 - times more probable to find a molecule in volume V_2 than in volume V_1 which is a part of the first. For $N = (m/M)N_A$ molecules this amounts to $P = (V_2/V_1)^N$. Inspecting the entropy change at free expansion one can define entropy through

$$\Delta S = k \ln P \qquad (6)$$

with $k = R/N_A$. Entropy increases as information is missed and disorder is increased [1], [4]. This approach to equilibrium is illustrated with Ehrenfest's model of dogs and fleas [5].

The described approach has been developed as a part of the curriculum for grade 10 - the last grade at which physics is taught - in our comprehensive school for pupils interested in humanities. (Pupils interested in science and mathematics, e.g., are taught a more detailed version in grade 11.) The main aim was to give the pupils at least a basical understanding of the operation of heat engines, refrigerators, heat pumps, of district heating and of energy degradation in general [6].

As for these pupils the development of concepts and laws of physics is of interest a historical survey is added [7], the material of which is not intended for testing. The work of S.Carnot is discussed who gave Eq. (1) following the analogy of water falling down a height difference on a mill-wheel with heat falling down a temperature difference (1824). Besides, Eq. (1) was in accord with experience of the builders of steam engines. At that time heat was considered an imponderabilium, i.e. matter with unmeasurable small mass. From work with calorimeters it

was inferred that heat is conserved in the same manner as mass. There are indications, however, that Carnot, at least subconsciously, distinguished the concepts of chaleur and calorique. If the first is understood as heat and the second one as entropy the present law results.

Carnot's work came through B.P.Clapeyron (1834) to the knowledge of W.Thomson - lord Kelvin who both for an ideal gas suggested Eq. (1) in differential form: $-dW = QdT/T$. Thomson used the equation $-dW/Q = dT/T$ to introduce the thermodynamic temperature scale (1848, 1849) which is used today. Thereby Thomson was aware of an inconsistency since he knew of Joule's experiment, but did not yet accept the equivalence of heat and work. He compared heat conduction whereby heat is conserved with the heat flow in a reversible cycle whereby work is done and wondered about "lost work" in conduction. (We know now that in conduction entropy is not conserved whereas it is conserved in a reversible cycle.) R.Clausius was the first to reconcile Carnot's equation (1) and Joule's result (2) (1850). Thomson then formulated the second law in the form that at a single temperature heat cannot be transformed into work (1851) and adapted his definition of the thermodynamic temperature scale to $Q_2/Q_1 = T_2/T_1$ (1854). Clausius gave the final general formulation of the second law (1854, 1862, 1863) and coined the term entropy (1865). The microscopic interpretation and Eq. (6) are due to L.Boltzmann (1871) and in a more general form (1877); in his honour k is called the Boltzmann constant.

The advantage of the proposed approach may be that pupils at the last occasion (in their last year of physics) in a limited time and with the use of simple calculus learn the implications of the second law essential for everyday life. On this ground they can grasp, at least vaguely, the way our present concepts evolved. Advanced material, e.g. calculations concerning the ideal gas, can be added if pupils are interested in it. Thereby the historical development and technical use play the role of motivation factors.

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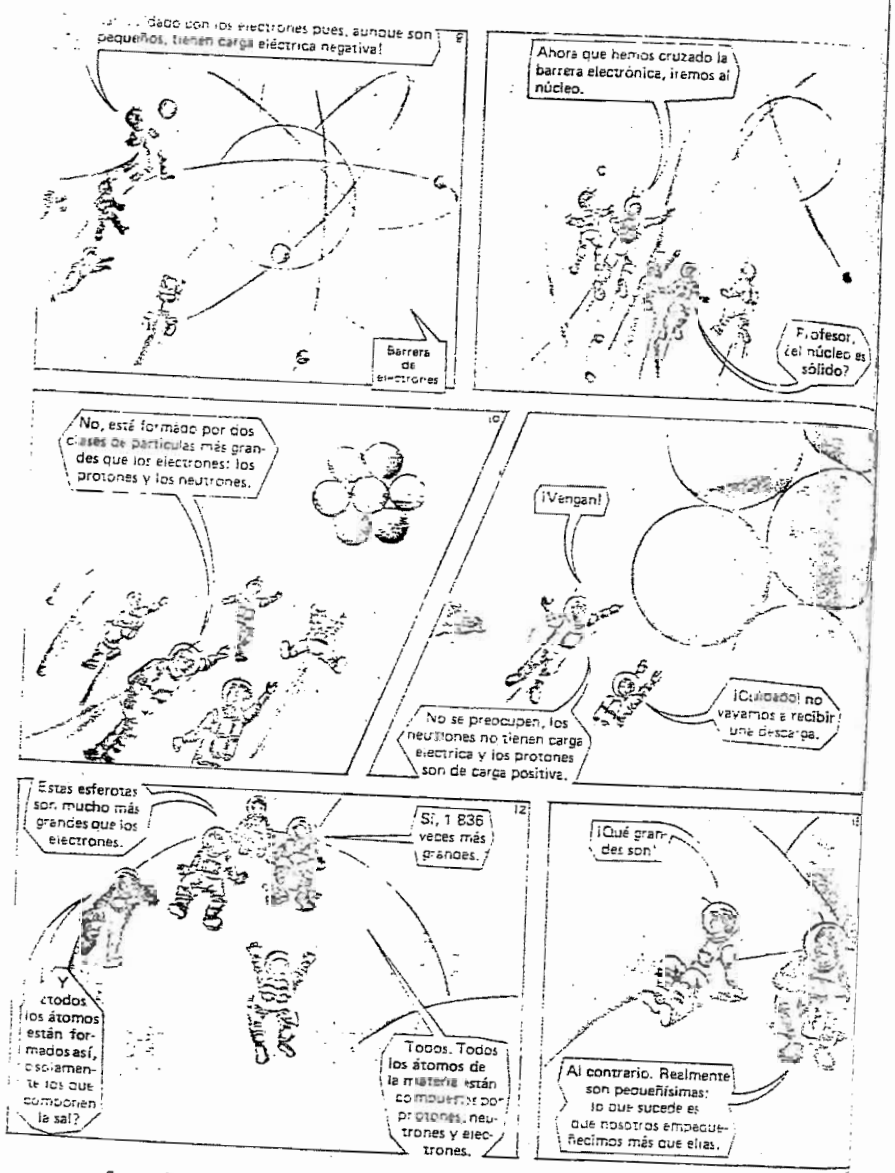
CHILDREN


pequeños, tienen carga eléctrica negativa!
Barrera de electrones
Ahora que hemos cruzado la barrera electrónica, iremos al núcleo.
Profesor, ¿el núcleo es sólido?
No, está formado por dos clases de partículas más grandes que los electrones: los protones y los neutrones.
¡Vengan!
No se preocupen, los neutrones no tienen carga eléctrica y los protones son de carga positiva.
¡Cuidado! no vayamos a recibir una descarga.
Estas esferotas son mucho más grandes que los electrones.
Sí, 1 836 veces más grandes.
¿Y todos los átomos están formados así, o solamente los que componen la sal?
Todos. Todos los átomos de la materia están compuestos por protones, neutrones y electrones.
¡Qué grandes son!
Al contrario. Realmente son pequeñísimas: lo que sucede es que nosotros empequeñecimos más que ellas.

from "Fisica Creativa V recreativa", grade 7, Mexico

LIFE WORLD AND SCIENCE WORLD

(Pupils' ideas about energy)

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The paper describes investigations, by various methods, of pupils understanding of the concepts of energy, particularly stored energy, and of conservation and dissipation. The results are interpreted in terms of a model of two different "worlds" in which pupils may think according to the occasion and problem - a Life World of everyday explanations and a Symbolic World of the explanations of science. Changes in teaching which might meet some of the difficulties revealed are discussed. A test of a new teaching approach shows that substantial improvement can be obtained if some form of the Second Law, emphasising dissipation and degradation, is taught at an early stage before Conservation of Energy.

1. INTRODUCTION

This paper describes investigations into pupils' thinking about energy. Almost all of the results were obtained by one of the authors - Joan Solomon - in her own school in connection with her own physics teaching. Some of the test results have also been repeated in another school. Individual and class discussions have been recorded and analysed. In addition, written tests have been set both before, and at different intervals of time after, teaching on energy. The researcher's detailed knowledge of and control over the teaching itself is a particular feature of the work.

The work is described in four main sections. Section 2 below describes investigations of ideas that pupils had before they had been taught about energy in physics lessons. Section 3 describes a model of pupils thinking about energy which distinguishes between the "Symbolic World" of the science lessons and the "Life World" of most of the pupil's daily experience.

Section 4 discusses pupils' ideas about conservation and about dissipation after receiving teaching about energy, whilst Section 5 discusses results of a change in the teaching adopted as a result of the outcomes of the first stages of the research. Finally, some of the implications of the work are considered briefly in Section 6.

2. PUPILS' IDEAS ABOUT ENERGY

Pupils in two schools were asked to give written answers to the following two questions:-

"What does the word energy mean?"

"Write 3 or 4 sentences to show how you would use the word."

The pupils tested were at ages 11, 12 and 13. All were following similar courses in science, which included no specific teaching about energy for these age groups.

The responses were first classified into three main groups according to the types of meaning that pupils associated with energy in their sentences.

The first group related energy to living - usually human - creatures. The common associations can be summarised in the following list:-

Living/people/life/growing
Fitness/health/illness/medicines/vitamins
Exercise/movement/activities/sports/work
Animals
In the body/blood/breathing
Food/carbohydrates/fat/sugar/glucose
Tired/out of breath/sweating/rest/sleep.

The second group related energy to non-living systems in the following ways:-

Electricity/batteries/power stations
Fuels/petrol/coal/gas/oil/nuclear power
Machines/cars/tractors/industry/moving objects
Lighting/heating/home appliances
Sun/fire/wind/waves/hydroelectric power.

The third group included universal statements about energy, common associations being -

Things/all things/everything/all.

Classification in this third category was made only if a sentence expressed an intention to generalise and was applicable across both of the first two categories. Examples of such sentences are:-

"A source of power which makes things grow or makes electric."

"Energy is something we use to move most things."

The results of this analysis are summarised in Table 1.

Table 1. Associations with the word energy contained in all of the responses of pupils at ages 11, 12 and 13 in two schools.

Sample	Number of Pupils	Living	Non-Living	Universal	Total Number of Responses
		Percentages of Total Number of Responses			
Age 11 Boys	45	70%	25%	5%	149
Age 11 Girls	53	93%	6%	1%	174
Age 12 Boys	40	52%	38%	9%	143
Age 12 Girls	60	70%	24%	6%	194
Age 13 Boys	41	35%	52%	13%	119
Age 13 Girls	39	50%	42%	8%	135

Girls' responses had predominantly human associations. For boys, human associations were limited to fitness and sporting activities, and were in the minority by age 13; this may be part of a tendency of many adolescent boys to avoid human and social implications (reference 1).

The second and third year pupils were also divided on the basis of ability, the top ability group including about half of the total in each case. Table 2 concentrates on the percentage of pupils giving statements

in the "Universal" Category.

Table 2. Percentages of Pupils Giving Universal Statements

Age Group	Ability Group	Number	Percentage giving at least one Universal Statement
11	All	99	8%
12	Top	53	42%
	Middle	47	4%
	All	100	25%
13	Top	43	51%
	Middle	37	11%
	All	80	33%

The changes with age could not be a direct influence of science teaching: they could be due to influence of other school teaching, of informal learning, or of a more general trend to move from concrete to formal thought about energy.

The large numbers of responses mentioning health, fitness, age and death recalled the old theory of Vitalism. Within the "Living-Human" responses, the responses could be further divided into strictly "Vitalist" responses concerned with health, growth, medicines, vitamins and life, and "Human kinetic energy" responses concerned with sport, activity movement, feeling tired, and food. At age 11, "Vitalist" responses predominated, at age 13 it was the "Human Kinetic Energy" type which predominated. "Exercise" presented a difficulty, which was explored in class discussion in the two schools. Pupils were asked which of the following two statements could be correct -

"Exercise Uses Up Your Energy"

"Exercise Builds Up Your Energy".

In both cases the voting was 20 to 2 in favour of the first statement, but a subsequent proposal that "Either could be right, it depends ..." attracted support from 10 or more pupils in each school.

The age 13 pupils were also asked "Can You Measure Energy?". Table 3 summarises the responses according to two categorisations of the pupils concerned. In both cases the results show statistically significant association between positive response to the question and progression from human associations to non-living or more general associations.

Table 3. Association of Yes/No Response to "Can You Measure Energy?"

3A - Association with "Living" responses and "other types"

	Pupils Giving Only Living Ideas	Other Ideas
Yes - can measure	7	40
No - can't measure	15	17

3B - Association with "Universal" Responses and Other Types

	Pupils Giving Only Living, or Non-Living or No Ideas	Pupils Giving Universal Ideas
Yes - can measure	32	18
No - can't measure	26	8

Further details of this particular study are given in a paper by Solomon (2). The broad picture is that children widen the range of associations of the term energy in this age range and that by age 13 a notion which is universal and quantifiable seems to be held by about one-third of them. One aspect not discussed here is that the results

must be related to the other uses in the language of the word used by science. So these results might not be replicated where English is not the native language (3).

3. SYMBOLIC WORLD AND LIFE WORLD

The idea here arises from the writings of Berger and Luckmann (4) and Schutz and Luckmann (5). In ordinary living, experiences have to be categorised and absorbed by us into our own "structures of meaning". These structures are developed and reinforced by communication and by the language which is our means of communication with others, and so acquire social value which makes them very important to us. Such socially reinforced structures constitute the "Life World" domain. This domain tends to be composed of many theories, each of application to a limited range of contexts. The theories are not necessarily consistent with one another and are not usally abstract in character.

By contrast, schooling in science will try to create new structures to replace these. These constitute a "Symbolic World" domain, characterised by few theories, mutually consistent and highly abstract in character.

Pupils will usually use Life World theories for all purposes except the work of school science lessons, and these theories will be those used by most parents and other adults. "Symbolic World" theories are peculiar to science lessons. To enter this world is to leave reality. To escape from it and return to the "Life World" is like waking up from a dream. The "Symbolic World" does not replace the "Life World", they co-exist, and a study of pupils' response to teaching may be regarded as a study of these two worlds and of the conditions in which they move from one to the other.

Tests taken by pupils after teaching of energy in their fourth year at secondary school (age 14) can be analysed in terms of this model. One example, discussed in detail by Solomon (6), illustrates the approach. Pupils were asked the following question -

> "An electric drill, working at a rate of 500 watts is used to drill a hole in a piece of wood. How much work could it do in 20 minutes? What energy changes are taking place?"

A diagram illustrated the situation. The analysis was concerned only with

the final part of the question. The teaching would have equipped pupils to answer in terms of a chain as follows:-

electrical energy ⟶ kinetic energy ⟶ heat energy.

Some pupils gave answers in these terms, but amongst them were a set who added to the formal terms some extra terms relating them to the electric drill, to friction in the hole drilled, to drill vibrations producing noise, and so on. These extra terms would be classified as part of the "Life World" and pupils linking these to the Symbolic World terms would be showing ability to transfer between the two. This gives two categories of response, Life plus Symbolic and Symbolic Only. A third category was also needed, to classify those whose answers were in the Life World only, talking of the switch, the cable, the plug, the cutting of the bit, the shavings, the friction and heating at the hole, but not relating these to energy terms or to any chain of energy changes. Table 4 shows how responses of 42 pupils were categorised in these three groups. These same pupils were asked a question in a similar form ("Name all the energy changes taking place in ...") but about a different situation ("...in a coal-fired steam engine or turbine" - again with a diagram), as part of an examination held 2½ months after the energy teaching. The responses are also in Table 4 only here the "Symbolic" and "Life plus Symbolic" have been collapsed to include all those who used energy concepts in their answers.

Table 4. Classification of Pupils by response to the Drill Problem, and Responses of these Sub-Groups 2½ months later

Nature of Response ⟶ / Test Occasion ↓	Life Plus Symbolic	Symbolic Only	Life Only or Wrong Response
Drill Problem - at end of teaching	11	25	6
Steam Engine Problem 2½ months later	↓	↓	↓
Using Energy Ideas	10	14	0
Life World terms only	1	11	6

These figures give statistically significant confirmation of two hypotheses, that with lapse of time, life-world meanings will tend to replace symbolic ones, and that the ability to cross over between the two domains will be a good prediction of future success and perhaps an indicator of a deeper level of understanding.

In another test, pupils were asked one question calling for "examples of energy" and another about "energy changes" taking place when a ball bounces. The numbers giving only Life-World responses were: 30 (out of 128) on "Examples of Energy" but only 1 on "Energy Changes".

The results are consistent with those reported by Viennot (7). The response given to a question may depend on which of the pupils' two worlds is evoked by it in those case where pupils cannot readily move between or relate the two worlds. Thus Viennot found that a general and abstract question - "If the same force acts on two identical masses, are the motions necessarily identical" was correctly answered by 80% of her sample, whereas a question showing three identical balls at the same height but moving along different trajectories with different velocities, led to only a 57% correct response rate to the question "Are the forces the same?"

4. CONSERVATION AND DISSIPATION

The recording and analysis of class discussions gave a rich variety of evidence about the ways in which pupils think about energy. These discussions were held both before and during teaching about energy in the fourth year (age 14).

For example, pupils often believe that the energy associated with food (learnt in biology lessons?) is not stored in it but is created by our bodies when we eat it. For fuels which we burn, the energy is created by the burning processes. More generally, stored energy is a confused notion because energy is thought of as a substance stored with food, or with coal, or with my body.

Conservation of energy is also a confused notion. One meaning is concerned with storage only - to conserve is to save up, to keep, to hold back. Another meaning is to save, to prevent waste - public campaigns to improve house insulation talk about "energy conservation" in this sense.

Neither of these meanings is the same as that implied by the Principle of Conservation of Energy. But a statement of that principle, in the form "Energy cannot be created or destroyed but can be changed from one form to another" also raises difficulties with pupils. The negative "not created" is easy to understand and accept, but the other negative "not destroyed" is not. As one pupil put it to his teacher.

> "That Principle of Conservation of Energy, Miss, I don't believe it. You know, when you have a battery and a lamp, and the battery has electrical energy, right? And it goes to heat and light in the lamp. Well, I mean, the heat evaporates and the light goes dim. So the energy has gone. It isn't there, is it?"

The following extract, from a class discussion, illustrates the point in another way.

Teacher	Can we actually run out of energy?
Pupil A	No you can't, can't destroy it.
Teacher	Can you run out of fuel?
Several Pupils	Yes, yes
Pupil B	Then you change the energy back.
Teacher	Can you change energy back into fuel?
Several Pupils	No, no
Pupil B	Yes you can
Pupil A	If you could, you'd be a millionaire!

The above example arose in a discussion provoked by a problem about a car running out of fuel, where pupils were asked to say what had happened to the energy. A systematic analysis of the discussions suggested that the conservation principle could be applied - whether correctly or not - in the following five ways:-

First	Using Life-World ideas only: "I mustn't use created or destroyed but still I do know that the energy is lost or burnt up".
Second	Using the idea that energy is stored in the original system: "If energy is not created or destroyed it must still be there, stored up in some way".

Third — Using the idea that energy is reversible, using the notion also that this relates to its being a substance: "If energy is conserved, it must turn up again in the same form as it was in the beginning".

Fourth — Using a model of Simple Transformation, often blindly from rote learning: "Like the Conservation Principle says, it can be changed, so it must have been".

Fifth — Using both ideas of Transformation and of Dissipation: "The energy must have been turned into some form which then leaks away, so that is why the object eventually stops".

The overall picture given by this part of the study was that pupils natural tendency to revert to Life-World explanations was enhanced here because teaching which concentrated on conservation was under a double difficulty. First that it seemed to fly in the face of all common experience, second that it depended on a term that had at least three related but distinct meanings.

5. TEACHING DISSIPATION

The conventional sequence in energy teaching has been to discuss work, then energy changes, leading to quantitative measures and calculations for energy in its various forms. This could culminate in statements about conservation. Energy dissipation or degradation might then be mentioned as an afterthought.

For teaching classes in 1982, a different sequence was adopted in an attempt to meet some of the problems exposed by the work described above, particularly in Section 4. After initial work on the ideas of work and on various forms of energy transformation, the teaching concentrated on the idea of energy dissipation. A variety of demonstration experiments, including a steam engine, a water siphon, a pendulum in which the damping of the swings was evident, and the expansion of CO_2 from a high pressure cylinder, was used to provoke discussion. This lead to an overall principle, stated in the following general form -

"In all energy changes, there is a running down towards sameness in which some of the energy becomes useless".

After this, work on heat loss and on world energy problems was developed. Finally, the idea of energy conservation was discussed, but in the light of the preceding work on dissipation.

One piece of evidence about the outcome can be quoted. A question set at the end of the energy teaching showed a golfer striking a ball, which bounced repeatedly as it travelled forward, with the heights of the bounces becoming successively smaller. The question was an open one "Describe all the energy changes that have taken place as completely as you can".

The same question was set in 1980, after the old teaching scheme, with no instruction on energy disspation, and in 1982 after the new one. Table 5 shows the percentages of pupils whose response fell into each of five main categories, one for those omitting to answer and four derived from the five described for the class discussion data in Section 4 above.

Table 5. Classification of Answers to describe energy changes for a bouncing golf ball at end of energy teaching in old (1980) and new (1982) sequences

Year	Number of Pupils	% in each Category				
		Omit	Life World	Storage or Reversible	Trans-formation	Transformation & Dissipation
1980	46	17%	9%	30%	30%	15%
1982	56	14%	12%	6%	29%	40%

The results show a well-marked improvement. The more able pupils particularly had shifted from the "Storage or Reversible Group" to the "Transformation and Dissipation Group". Of the 22 in this group in 1982, 19 also gave a correct statement of the Principle of Conservation of Energy in the same test, compared with 9 out of the 16 in the "Transformation Group"

and 6 out of the 18 in the first three groups. Thus, teaching about dissipation had not caused obvious confusion about the Conservation principle. There was also strong association between ability to state the "Running Down" principle and ability to use it, as characterised by the categorisation of responses to the question described above.

6. CONCLUSIONS

The discussions of the significance and interpretation of the above results have been kept brief and are left largely to the reader. However, certain general conclusions are strongly supported by the work.

First, if we want pupils to learn any physics principles effectively, we must find ways to help them to link the Symbolic World of our physics to the Life World of their everyday experience. In order to do this, we need to study and understand this Life World for the areas of experience which relate to the principles being taught.

Secondly, for teaching about energy, the above principle must lead to the conclusion that dissipation and transformation of energy should be taught first, and that the Conservation Principle comes later. It should also be mentioned that there are good general arguments within engineering thermodynamics for teaching a Running Down principle in its own right (8). So the Second Law comes first, and we should teach it, not only because we want it to be understood for its own sake, but also because appreciation of it is a necessary condition for pupils to make sense of the concept of energy and of its conservation.

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THE CONCEPT TRIANGLE ENERGY-INFORMATION-ORDER IN THE HEADS OF OUR STUDENTS

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1. Introduction

Discussions among physics educators in the last years about teaching the concept of energy and the difficulties connected with it revealed a strong deficit of school physics in teaching everything a r o u n d energy that could make the students understand the concept itself. The First Law of Thermodynamics refers to e n e r g y q u a n t i t y alone; this law, and so the quantitative aspect, is in the centre of interest in school physics up to now. However, the q u a l i t y of energy, its "value", "effectivity", "exergy" or whatever expression might be used, which is connected with the Second Law, with Entropy, Information, Order, is largely neglected in school teaching. This seems mainly due to the fact that science education is still strongly basing upon the classical dualism of the beginning 20th century: the dualism of m a t t e r on one side, e n e r g y on the other.

In the meantime,however, science is increasingly forced to take a third basic category of our world into consideration: the category of i n f o r m a t i o n . This category which is closely interlinked with the concepts of entropy/negentropy, probability/uncertainty, disorder/order, adds a new dimension to the other two categories and leads to a better understanding of both energy and matter by viewing the "substance" (the elements of our systems) from the s t r u c t u r a l aspect (the relations between the elements).

Hence it seems worthwhile to extend the teaching of energy to the teaching of information, or entropy respectively,

in order to develop a full understanding of energy. This does not necessarily mean a "more" in teaching, but may even mean less and easier teaching, because there is, in fact, some evidence that the concepts of information and order are easier to understand than the concept of energy, and that, consequently, the Second Law might also be easier to teach than the First Law (see the article of DUIT in this volume).

In this paper, students' notions about the concepts of e n e r g y , i n f o r m a t i o n and o r d e r and their triangle relation are investigated. The purpose is to know what is present in the heads of our students, before we start to make plans about a new approach to "energy" that might be more succesful in school a n d everyday life than the previous one.

2. Methodological remarks

The concept investigations of the author are basing on the general conviction that it is not the scientific concepts, consisting of a t e r m (word, designation) and its standardized m e a n i n g , that count in everyday life, but rather the tripartite structure of term, standardized meaning and the f r a m e w o r k o f p e r s o n a l a s s o c i a t i o n s . This tripartite structure obviously active in everyday life has been described as the "burr model" by the author (SCHAEFER 1979, see fig. 1). The model demonstrates 3 characteristic properties of a concept: 1. There are "kernels", "seeds" of the burr carrying the basic information: the l o g i c c o r e of attributes characteristic of a certain class of things, structured by superordinate/subordinate relations (the vertical lines in the scheme) and by system/part relations (the horizontal lines). 2. There is a "stalk" to carry the whole fruit and to fix it to the plant: the term or designation which serves as a "handle" to make the concept operable. 3. There is, finally, a framework of hooklets and hairlets making the fruit adhesive so that it may stick to a carrier and be

transported to some place of relevance (i.e. of germination): the framework of personal associations that make the concept adaptive to different situations of life relevant to the person so that the logic core can be memorized at all in different contexts and then be utilized.

The investigation of the tripartite concept structures of energy, information, and order was performed with the term (the key-word) as stimulus, free definitions and multiple-choice responses as indicators of the logic core, and free associations as an indicator of the associative framework.

Accordingly, the results given in the following will consist of four kinds of presentations: a) the most frequent specific associations (sector diagrammes); b) the distribution of all free associations over general categories ("association profile"; polar diagrammes); c) the distribution of all definition fractions over the same categories ("definition profile"; polar diagrammes); and d) the percentages of multiple-choice responses.

3. Empirical results

3.1. The concept of ENERGY

3.1.1. The Associative Framework

As fig. 2 shows, in the North-German sample of 16 to 23 year olds the most frequent association to the key-word "energy" is f o r c e , not work, as could be expected after 3 to 5 years of physics teaching. "Work" covers only the 5th rank. Although 9 of the 14 most frequent associations have a clearly physical connotation, most of them (current, heat, atomic power station, light, etc.) proved, according to an interview held after the test, n o t to be mainly a product of physics teaching, but rather a product of everyday life, especially through the mass media. So the high number of physics-like associations should not lead

us to the illusion that physics teaching is acting very effectively upon the associative framework. This warning is supported by the fact that "work", the physical equivalent to energy, is only on the 5th rank, although in physics teaching in West-German schools this equivalence is elaborated with much effort.

This is not necessarily so, as a comparison with a corresponding population in the Philippines shows (fig. 3). Here "work" is on rank 1, and "force" on rank 6, - just opposite to the German situation, and in better accordance with the priorities taught in physics. Furthermore, here the associations evidently caused by physics instruction ("kinetic", "potential", "nuclear", "mechanical", "solar", "physics/physical") together cover about 36 % of the most frequent associations, whereas in the German population they amount only to 20 %. The effect school teaching has on the associative framework of energy seems to be higher in the Philippines. This is in accordance to other observations, e.g. on the concepts of health, ecosystem, environment.

Another remarkable result shown in fig. 2 is the fact that connotations of b i o - energy are very rare ("dextrose", "strong/strength", "sports" on the last 3 ranks), although the test-population consisted mainly of those students who had chosen b i o l o g y as their central scientific subject, and who in their studies had very intensively been taught phenomena of bio-energy (photosynthesis, dissimilation, energy-carriers, enzymatic reactions etc.) This, again, demonstrates that school instruction apparently is not very effective in West-Germany with respect to the associative framework of energy. The concept periphery is neither adequately composed of those "hairlets and hooklets" which lead to the right p h y s i c a l expectations nor those which make the citizen aware of the fact that b i o - energy is the most important form of energy for mankind, and has ever been since the evolution of Man. It should, for instance, be kept in "mind" (i.e. in our associations) that the amount of annual bioenergy produced by means of photosynthesis on our earth is about 3 t i m e s as much as the amount of energy technologically used by Man! This relation should, at least approximately, be reflected in the concept periphery of "energy". However, the contrary is the

case: The technologically used (or discussed) energy forms predominate. As DUIT and ZELEWSKI (1979) showed, German students in the age of 13 are thinking of energy as being some kind of "luxury article" relevant for our civilized life. They were apparently not aware of the fact that energy (e.g. in form of our food) is a b a s i s o f l i f e , independent of the degree of civilization and luxury. Comparing with fig. 3 we have to state that also the Philippine population does not have the appropriate associative notion if bio-energy. "Food", "oil", "strong/strength" together cover only about 15 % of the most frequent associations; the associative framework of the concept, in the Philippines, is overloaded with physical/technological elements. Biology teaching seems to have failed with respect to energy, like in West-Germany.

The results concluded from the sector diagrammes, fig. 2 and 3, are reconfirmed by the polar diagrammes fig. 4 and 5 which show the distribution of a l l given associations (not only the most frequent ones) over certain categories. Only 13 % (in the Philippines 16 %) of all associations fall into the biological category, whereas the majority (66,4 % in West-Germany, 53 % in the Philippines) have to be grouped under physics/technology/non-living nature and 7 to 9 % under chemistry. So in both populations energy has mainly a n o n - l i v i n g c o n n o t a t i o n , although "hooklets and hairlets" towards human life are clearly represented in the categories traffic, private life, energy politics, psychological aspects, and pos./neg. emotions. It is interesting to observe that in both populations the positive emotional reaction to energy ("hope", "progress", "relief", etc.) is higher than the negative one, and that this is more so in West-Germany than in the Philippines. Furthermore, there is a striking amount of associations in the categories "private life" and "energy politics" in West-Germany, whereas in the

Philippines the amounts are low. Energy, in the spontaneous reaction of citizens, seems to play a public and private role in industrialized West-Germany which is stronger than in the developing country. Strange enough, this is not true in the category of "traffic", although most of the tested students were confronted with the energy side of traffic every day. Interviews with the students showed that they were connecting traffic problems with concrete associations such as "gasolene", "oil", "traffic taxes", "prices", and only very rarely with the highly abstract association "energy" (which one student sarcastically called a "laboratory concept"). Still, the same tendency towards concreteness should appear in the categories "private life" and "energy politics"; which is not true. Up to the present date there is no satisfactory explanation yet why the category "traffic" drops out of all expectations.

3.1.2. The Logic Core

As fig. 4 already shows, the definition profile (permanent li e) differs from the association profile in the normal, typical way: the category of "formal terms" (system, structure, function, relation, all, noone, never, etc.) is strongly filled up as well as the category which is scientifically attributed to the concept (here "physics/technology"), whereas all other categories are markedly reduced by means of the filter process of thinking. The reduction, however, is lowest in the categories "biology" and "psychological aspects" what may indicate that r e f l e c t i o n upon energy possibly leads to more awareness of the bio-energetic side.

A multiple-choice test differentiated the responses of the students in more detail and discovered the relationship between ENERGY, INFORMATION and ORDER with respect to the investigated concept triangle (Table 1). It comes out that West-German students in the age of 16 to 23, although having studied physics at school on the lower secondary level for

Table 1: Multiple-choice test for the concept of ENERGY.
Biology students, age 16 to 23, n=118.
The figures in squares are percentages of the whole population.

1. [43] The world is mainly organized by energy
2. [31] The world is mainly organized by forces
3. [7] Energy and force are the same
4. [5] Energy and work are the same
5. [57] Energy means the ability to do work
6. [34] Energy means stored work
7. [17] Energy means stored power
8. [7] Energy means the product of power and time
9. [49] Energy is necessary to reduce entropy
10. [16] Energy is necessary and sufficient to increase entropy
11. [7] Energy has nothing to do with entropy
12. [26] Energy is a physical vector (directed variable)
13. [39] Energy is a physical scalar (undirected variable)
14. [27] Energy q u a n t i t y alone determines the working capability of a system
15. [27] Energy q u a l i t y alone determines the working capability of a system (energy quality means the value of energy, the energy level)
16. [76] Energy nowadays is preferably measured in Nm (Newtonmeter) or J (Joule), respectively
17. [15] Energy nowadays is preferably measured in kW (Kilowatt)
18. [50] Quality of life clearly grows and falls in correspondence to the quantity of the available energy
19. [42] Quality of life is not clearly correlated to the quantity of energy
20. [32] Quantity of energy and quantity of information are correlated to each other:
the correlation is positive [19] negative [10]
21. [60] Quantity of energy and state of order of a system are correlated to each other:
the correlation is positive [43] negative [15]
22. [0] No answer valid

3 to 4 years and specializing at present on biology, have a poor understanding of the relationship between energy and entropy, energy and information, energy and order, and also energy and the quality of life. This is also confirmed by answers no. 1/2 and 12/13 which show that a great number of students have no clear conception of the scalar, i.e. n o n - d i r e c t i v e nature of energy. They seem never in their school resp. university life to have been taught that energy is a "willing servant" for everything and has no direction in itself. The d i r e c t i o n of processes is always determined by a s t r u c t u r e in the system, by order, information, entropy or whatever additional variable we may choose. Not even the clear distinctions of energy and force (which is now about 100 years old), work and power, quantity and qualitiy, kilowatt and kilowatthour are present in the minds of all tested students, although there is much effort spent in school physics on elaborating these distinctions, up to learning corresponding formulas by heart.

The energy concept is not well understood, and very poorly integrated in a scientific concept structure necessary for really understanding what is going on in our world!

STUDENTS IN THE AGE OF 13 ARE THINKING OF ENERGY AS BEING SOME KIND OF "LUXURY ARTICLE" RELEVANT FOR OUR CIVILIZED LIFE.

Gerhard Schaefer

3.2. The concept of INFORMATION

3.2.1. The Associative Framework

Among the 12 most frequent associations to the stimulus "information" there is none pointing into the direction of "entropy" (or better: negentropy), i.e. the s y n - t a c t i c dimension of information concerning the s t r u c t u r e of a system (fig.6). All 12 guiding associations belong to the p r a g m a t i c dimension, the dimension of communication between a "sender" and a "recipient". The only association which could mean some syntactic view is "knowledge"; however, an interview after the trial showed that the test-persons did not mean with "knowledge" the structure of engrammes in our brain, but just "stored messages" (what again means the pragmatic dimension). The only association having a more s e m a n t i c direction, independent on a recipient (i.e. a structure as a c a r r i e r of an assigned m e a n i n g), is "news, message", which is on the 8th rank.

With regard to the investigated concept triangle energy/ information/order we can already conclude from fig. 6 that there seems to be no connection on the associative level between information and energy on one side, information and order on the other.

Fig. 7 (dotted line) demonstrates the total association profile of all given associations. It repeats, on the more abstract level of general categories, the above drawn conclusion: Most of the associations are of the p r a g m a - t i c kind. Only 6 % are pure word associations (being some variant of the word "form", like formation, formal, formula etc.) which do not indicate the syntactic dimension of a system. 12 % are formal associations like "dependance", "model", "constellation", "little", "much", very few of which really indicate a syntactic view of information (e.g. model, constellation, entropy, structure, regulation, see fig. 10). So the method of free associations reveals already

a considerable gap in the understanding of "information" among the West-German students.

3.2.2. The Logic Core

The definition profile (permanent line in fig. 7) shows the reduction in several categories which is typical for definitions, and a constancy or even increase in those categories which are regarded as "essential" by the students, here the formal category, the pragmatic category of information transfer/ message, and the subjective area ("knowledge", "thinking", "imaginations", etc.). The strong reduction in the category information techniques/computers shows that there is apparently little notion of the purely syntactic, objective side of information which manifests itself best in its technical application.

In spite of the strong increase of f o r m a l elements in the definitions, as compared with the associations, there are only very few elements pointing into the syntactic direction ("form, shape of something"; "means of decision in control systems"; "theoretical subject matter which need not be senseful"; "a factor in producing order"; "precisely defined unit of knowledge"; "... is in everything; every state, individual, process"). There was no one definition connecting information with energy, e.g. by means of "energy quality", "energy value", "entropy" (cf. table 4 in chapter 4).

In order to differentiate the answers given by definition and to elucidate the logic core of the concept more precisely, a multiple-choice test was used. The result is shown in table 2.

It comes out as expected from the free associations and definitions:

Information is very rarely regarded from the syntactic aspect (see answers no. 7/8, 9/10, 13/14). It is a pragmatic

Table 2: Multiple-choice test for the concept of INFORMATION.
Biology students, age 16 to 23, n=116.
The figures in squares are percentages of the whole populati

1. [17] Information is the "in-formation", the impressing of a form in a material carrier
2. [39] Information is not bound to matter as a carrier
3. [7] Information is the scientific expression for "spirit"
4. [47] Information is the same as "message"
5. [51] Information is the p r o c e s s of sending a message
6. [0] Information is the same as "order" (I=O)
7. [18] Information is originated by order (O→I)
8. [54] Order is originated by information (I→O)
9. [5] Information generally means "structure" (as a neutral, mathematical concept)
10. [45] Information only means such a structure which has a specific meaning for a "receiver"
11. [32] Information only means such a structure which a "sender" has attributed a specific meaning to
12. [51] Information in 10 and 11 does not mean the carrying structure itself but only its meaning
13. [2] Information means entropy
14. [5] Information means negative entropy ("negentropy")
15. [71] Information is frequently measured in bits
16. [15] Information can only be measured in bits
17. [0] Information generally can be measured also in Nm · sec
18. [58] Information, in the long run, leads to Man's liberation from pressures
19. [19] Information only transitionally leads to Man's liberation, but in the long term to increasing stress
20. [18] In a closed physical system the sum of all information remains constant (conservation law of information)
21. [67] Information is able to disappear completely and to re-originate as well (there is no conservation law of information)
22. [0] no answer valid

variable of communication between a sender and a receiver in the minds of most students (see 4/5, 10/11/12). Its spiritual (non-material, non-substantial) nature is partly recognized (answers no. 2/3, 9/12, 21), however, the full consequence of this notion is apparently not realized (controversial marking of 2 and 3, although the two answers are very similar in their meaning). There is even some feeling of a s u b s t a n t i a l character (conservation law) of information (answer no. 20) which resembles the numerous attempts in modern physics to describe "entropy transfer", "entropy uptake and removal", "entropy storage" in the sense of entropy being a substance-like variable underlying a conservation law.

The reaction to answers no. 18 and 19, finally, reconfirms the findings of fig. 7 about the a m b i v a l e n c e o f f e e l i n g s about information. There is almost the same amount of negative as positive emotions about information among our young people which correspond to the reactions towards "order" (fig. 9), but differ from those towards "energy" (fig. 4 and 5) which are predominantly positive.

3.3 The concept of ORDER

3.3.1. The Associative Framework

Fig. 8 demonstrates the 12 most frequent associations to the key-word "order". It is striking to see that only about half of these associations are coming from the concrete level of everyday experience (garden, room, police, clean, etc.), but that the other half (hatched sectors) is covering the field of very abstract terms (rule, sequence, structuring, law, system). This gives already a hint that the concept of order is highly filled with abstract, formal elements, in contrast to information (fig. 6) and energy (fig. 2 and 3).

The whole spectrum of associations (fig. 9, dotted line), however, does not show a particular peak in the formal category, although in this category those associations which are specifically used in mathematics and physics (e.g. set, relation, element, structure, entropy) and which have separately been counted on the axis "math. and physical area", have also been included. So the highly formal nature of the associative framework of "order" only appears in the 12 leading associations.

Again, as in the concept of "energy", we find both in the leading associations and in the total spectrum a remarkable lack of biological associations. This is particularly striking in view of the fact that the testpopulation consisted mainly of biology students who in all their studies were facing the phenomenon of b i o l o g i c a l order day for day. And again: the t r a f f i c category is almost empty, although traffic order, traffic rules belong to the daily experience and problems of the students. It is quite reasonable to assume that those categories which are most common and essential in everyday life should have a high occupation with associations. This is certainly true for "family / house order", "state / society", "emotions" (both kinds, as order always is ambivalent), and "order in the mind", but it is not true here for the categories "mathematical and physical area" (as the students did n o t specially study mathematics and physics), "life / bio-systems" (the students' specific subject), "arts / esthetics", and "traffic" (permanent realms of experience). There is no general explanation yet for this discrepanay. One conclusion that may by drawn from figures 8 and 9 is that biological instruction in school and university does apparently n o t contribute essentially to the concept periphery of "order". This is rather alarming, as one of the basic notions of life is that life creates order from disorder and counteracts entropy.

3.3.2. The Logic Core

The great number and percentage of formal associations among the 12 leading associations is reflected again in the definitions (fig. 9, permanent line). In all categories the percentages of definition elements are reduced to almost zero, except those of the highly formal kind. That means: almost all definitions are operating on a very abstract level; "order", as reflected by the 16 to 23 year old students, is a concept much more abstract than energy (fig. 4) or information (fig. 7). This corresponds with the high abstractness of the related concepts of disorder and entropy. It also corresponds with the daily experience which can be made with students of all age levels on the illustration of "order" and "disorder": Whereas the t h e r m o d y n a m i c disorder, in the sense of equal distribution or homogeneity, can easily be illustrated by means of diffusion of a coloured solution, this state of maximal thermodynamic "disorder" in the imagination of students normally appears to be a state of maximal o r d e r. In their minds there are t w o maxima of high order: 1) the inhomogeneous, specially structured system, and 2) the absolutely homogeneous, "unstructured" system. To produce either of them needs special effort, special energy, as the students know from their private life, and both extreme cases are equally unlikely.

If this is so, it is not surprising that the students ever again have difficulties to believe that nature, by itself, is moving towards the state of absolute thermodynamic disorder, i.e. u n l i k e l i h o o d. They rather expect nature to "get stuck" somewhere between the two extreme cases, i.e. to move to the point t h e y assume to have the highest probability.

Insofar order and disorder are no objective concepts being fixed for all times, but relative descriptions of a system dependent on the degree of probability the observer attributes to the system. And this, again, means that order and disorder are not simple phenomena which can easily be demonstrated by experiment, but that they have to be elaborated as r e l a t i o n a l concepts on an abstract level.

Table 3: Multiple-choice test for the concept of ORDER.
Biology students, age 16 to 23, n=118.
The figures in squares are percentages of the whole population

1.	23	Order is the clear structuring of our internal and external world
2.	72	Order is no objectivable concept pertaining to our environment, but only designates a property of our subjective world of imagination
3.	15	Order is a pure fiction, not existing in objective reality
4.	69	Order is able to originate in the material world by itself (without the influence of Man)
5.	13	Order, in the material world, can only origninate under the influence of Man
6.	55	Order only can originate with support of energy (energy is necessary)
7.	31	Order only can originate on the basis of material carriers (matter is necessary)
8.	56	Order only can originate by means of information (information is necessary)
9.	0	Order means the same as information
10.	28	Order does not mean the same as information, but can be measured by information
11.	14	Order means the same as structure
12.	32	Order means the same as system
13.	5	Order means the same as entropy
14.	39	Order means the contrary of entropy
15.	28	Order can be measured by entropy
16.	17	Order, in our life, essentially means pressure and submission
17.	35	Order, in our life, essentially means freedom, relief, facility
18.	14	Education towards order means self-alienation of Man
19.	33	Disorder increases creativity
20.	0	No answer valid

The relativity of order/disorder is also pointed out by FALK 1983 (see his paper in this volume). It is furthermore demonstrated by the results of the multiple-choice test (table 3). Answer 2, in particular, which has been marked by 72 % of the population proves that most of the students regard the phenomenon of order to be a subjective phenomenon which purely exists in our imagination and hence is extremely relative. However, 15 % of the students shrink back from the consequent conclusion that order would be then a mere fiction without an objective reality (answer no. 3). The uncertainty in the test-population about answers 4 and 5 show that the students really are in doubt about the question what "order" is in general. Otherwise it could not be explained that b i o l o g y students mark answer 5 which contradicts all biological experience about evolution.

Answer 6 shows that 45 % of the students are uncertain bout the role energy has in the generation of order. The same is true for answers 8/9/10 which examine the relation between order and information. There is no clear majority of students deciding for one of the answers, although at least answers 8 and 10 have to be regarded as correct.

The higher positive marking of answer 12 as compared with 11 proves a clear uncertainty about the concepts of "structure" and "system", and answers no. 13/14/15 prove an uncertainty about the relation between order and entropy (although 14 points in the right direction of an anticorrelation between thermodynamic order and entropy). Still, no. 14 is not quite correct, as order "is" not the contrary of entropy, but can be measured by entropy (answer 15, which, however, has a lower percentage of marks). In all these cases it has to be considered that the students were thinking of the e v e r y-d a y phenomenon of "order" (see above) and n o t of the thermodynamic concept. So it is not surprising that many of the answers contradict each other, and no clear picture comes out.

Finally, answers 16 to 19 reconfirm the result of fig. 9 showing a remarkable ambivalence of emotions. The students

perceive the positive and the negative sides of order in a comparable degree, although a great number (almost half of the population) do not make any decision at all and seem to be uncertain again.

4. The Concept Triangle

Comparing the results gained with the three concepts we find some a s s o c i a t i v e b r i d g e s between them in the words "knowledge", "energy", "entropy", "enthalpy", "structure", and "regulation" (fig. 10). The percentages of their occurrence, however, are so low (between 0 and 2.4 %) that the a s s o c i a t i v e t r i a n g l e has to be regarded as extraordinarily weak and can almost be neglected.

This is different on the level of logic cores, where precise relations between the 3 concepts turned out via l o g i c b r i d g e s between information/energy, information/quality of life/energy, information/entropy/energy, information/entropy/order, information/order, information/structure/order, and energy/order (fig. 11). The single results have already been reported in the previous chapters (multiple-choice tests) and are here only recompiled in order to facilitate a survey and to give a whole picture of the l o g i c t r i a n g l e of concepts. The picture is not clear, as pointed out earlier, and contains many uncertainties and contradictions. As a matter of fact, we have to conclude that there is no real "triangle" of the 3 investigated concepts in the minds of the tested West-German biology students, neither on the logic level nor on the associative level.

The author's suggestion to build up such a triangle is through the concepts of entropy and information, both basing on the concept of p r o b a b i l i t y (see article of SEXL in this volume). According to the formulas for information (SHANNON's equation) and entropy (BOLTZMANN's equation) the probability of the state of a system is the key-variable to describe the new dimension of energy which deserves our full attention. To-day it is the probability by which system structure

can be quantified, independent of our decision to call this dimension "order" or "information" or "negentropy". The distance from the state of greatest probability would then be called information resp. negentropy, or even "order", if we abandon the old thermodynamic meaning of inhomogeneity. As in the area of life "order", in the thermodynamic sense of inhomogeneity, can have a h i g h probability (because of the "trick" of autocatalytic reproduction), the popularized physical version is not true that "our world is moving towards a state of maximal disorder = homogeneity". This version has to be replaced by the better one: The world is always moving towards a state of h i g h e r p r o b a b i l i t y (and this can even be a state of higher "order", as in the case of living systems!).

Considering energy to be embedded in a surroundings which has such a probability, we can atrribute this property of the surroundings to the concept of energy, and sonsequently we obtain a more complex concept of energy which is something like "energy in a context", "context energy", "energy triangle", or whatever. E n e r g y a m o u n t, as formulated in the First Law, and energy quality or e n e r g y v a l u e, as formulated in the Second Law of thermodynamics, are two ways of consideration of the same thing: the first one is the product of isolation of a phenomenon, the second one the product of its i n t e g r a t i o n in the context of the total system.

Going beyond physics we then pass different system borders and move, from physical contexts, on to cybernetic, physiological, ecological, economic, and finally social context .Each such system has its own structure, probability, entropy, information, and according to them,the same amount of energy gets quite different "values".

Table 4 shows a comparison of such values. It demonstrates the relativity of energy in different contexts. Maybe we shall be able in the near future to quantify these "values" through the aid of the concepts "entropy" or "information". This would take us quite a good step ahead in the hot political discussions about the question "more energy, or less energy". It is lastly the q u a l i t y that counts, and this means: information; (or entropy, respectively). It is information (or entropy or "order")

Table 4: Valuation of ENERGY ("Energy qualities").
++ means high value, + medium value, 0 no value, - negative value (destructive)

Energy value / Example (Energy carrier)	Physical Value	Cybernetic Value	Physiological Value	Ecological Value	Economic Value	Social Value
Sunlight	++ (solar energy plants; clouds→rain →dams →electricity)	++ (signal effect; orientation of animals and plants)	++ (photosynthesis)	++ (via green plants)	++ (food energy, recent and fossile fuels)	++ (out-of-door social events, vacation, etc.)
Pure cane sugar	++ (chemical energy→other energy forms)	0 (cane sugar normally not used as information carrier)	± (energy supply: +; health, e.g. teeth: -)	- (destruction of ecosystems by sugar cane monocultures)	++ (high profit)	± (sweets as presents:+; sweets as substitute for parental love:-)
Plastic (e.g. polystyrene)	++ (chemical energy→other energy forms)	+ (plastic toys, plastic records and tapes)	0 (plastic not digestible)	- (plastic production, plastic garbage, pollution of ecosystems)	++ (high profit)	+ (toys; pre-fabricated houses; furniture: +. Distance from natural products: -)
Electricity	++ (→all forms of energy)	++ (used for all forms of communication, like telephone, television, radio).	0 (no physiological utilization).	+ (application environment positive: +, production via coal, oil, atomic power stations: -)	++ (high rentability, high profit).	+ (ambivalence of the use of household machines and of electronic products)
Fresh fruits	0 (too little energy, no utilization)	+ (stimulus for senses)	++ (easily digestible)	++ (natural prod from polycultures)	++ (can make high profit)	++ (group fostering effect of fruits in all kinds of meals)

that determines the d i r e c t i o n of processes in our world; energy alone (the quantity) is a willing servant for everything.
In education this c o n t e x t d i m e n s i o n of energy, the "triangle", seems to become more important than the concept of energy alone.

Acknowledgement

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> 'THERE IS, IN FACT, SOME EVIDENCE THAT THE CONCEPTS OF INFORMATION AND ORDER ARE EASIER TO UNDERSTAND THAN THE CONCEPT OF ENERGY, AND THAT, CONSEQUENTLY, THE SECOND LAW MIGHT TO TEACH THAN THE FIRST LAW.
>
> Gerhard Schaefer

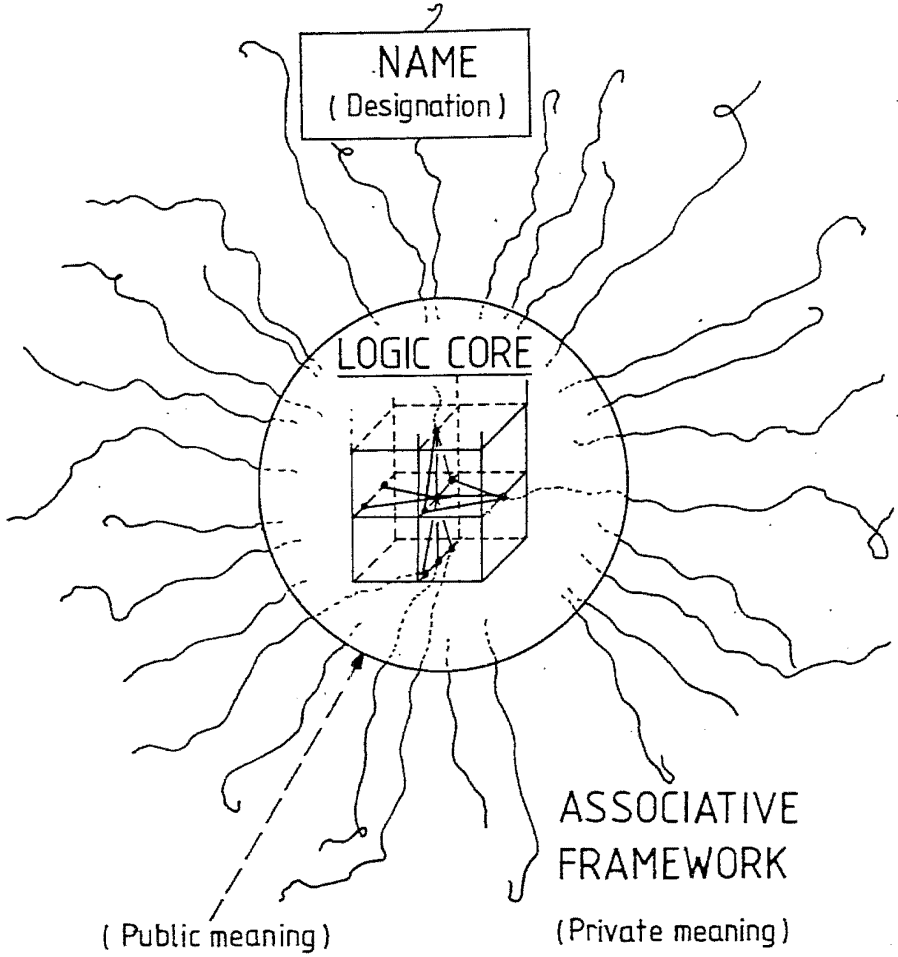

Figure 1. "Burr Model" of a concept demonstrating the tripartite structure. This psychological units is active in evryday life.

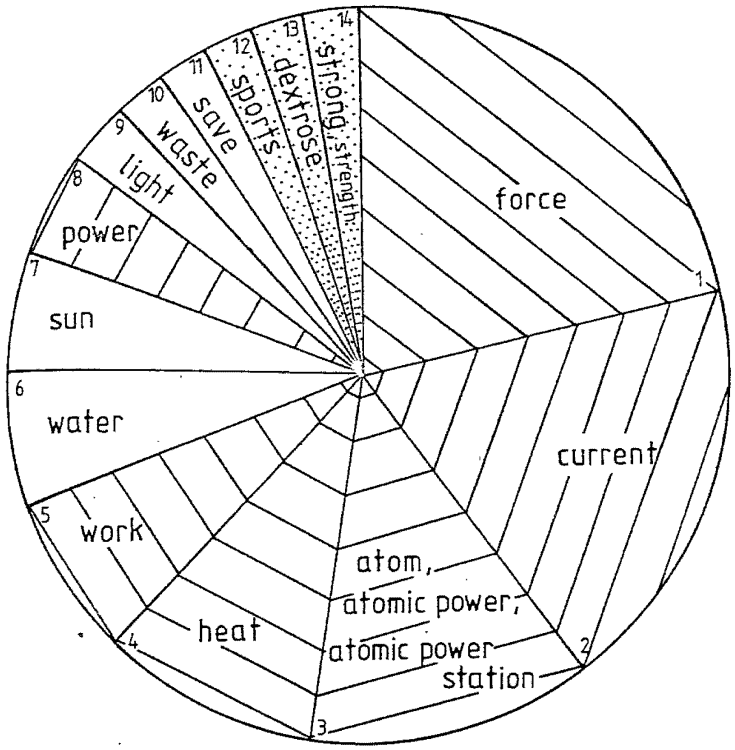

Figure 2. The 14 most frequent free associations to the key-word ENERGY, in their relative distribution. Biology students, North Germany, n = 156. Hatched areas: Associations closely connected with physics teaching. Blank areas: associations from everyday life outside school. Dotted areas: associations closely connected with biologycal subject matter.

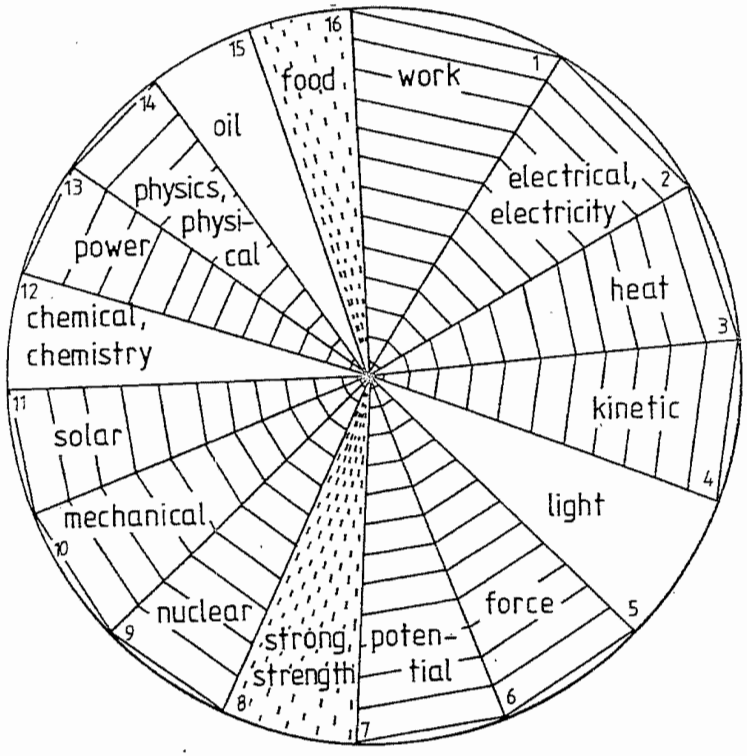

Figure 3. The 16 most frequent free associations to the key-word ENERGY from a Philippine high school population, age 16 to 18, n = 112.

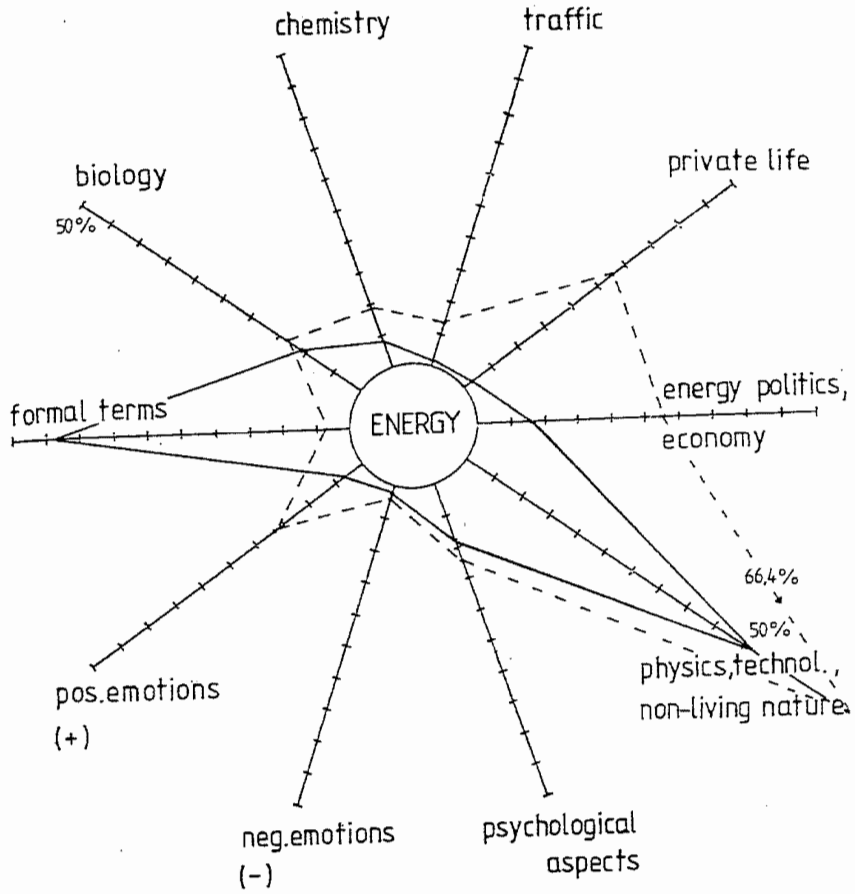

Figure 4. Total association profile (dotted line) and definition profile (permanent line) in North Germany. Population as in Figure 2.

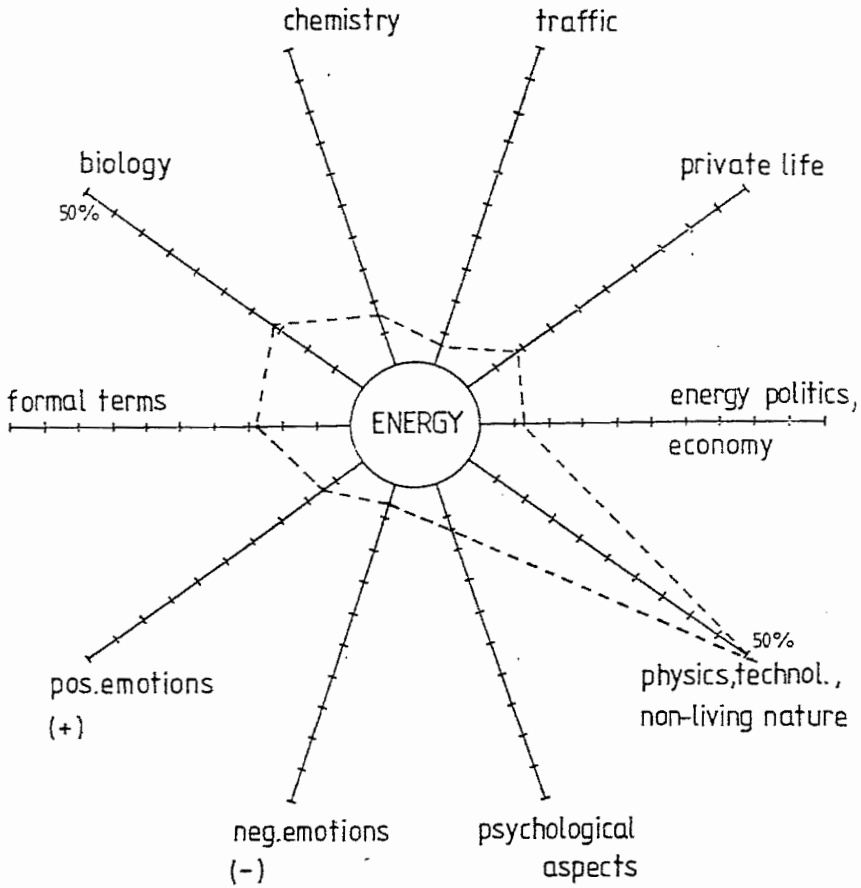

Figure 5. Total association profile in the Philippines. Population as in Figure 3.

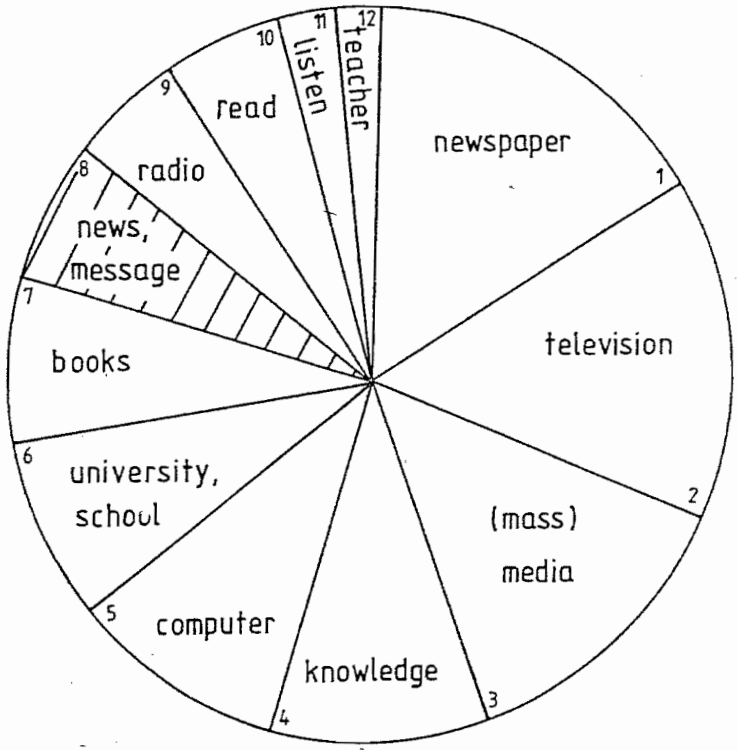

Figure 6. The 12 most frequent free associations to the key-word INFORMATION, in their relative distribution. Population as in Figure 2. Hatched area: the only association leading to a motion of the semantic dimension of information.

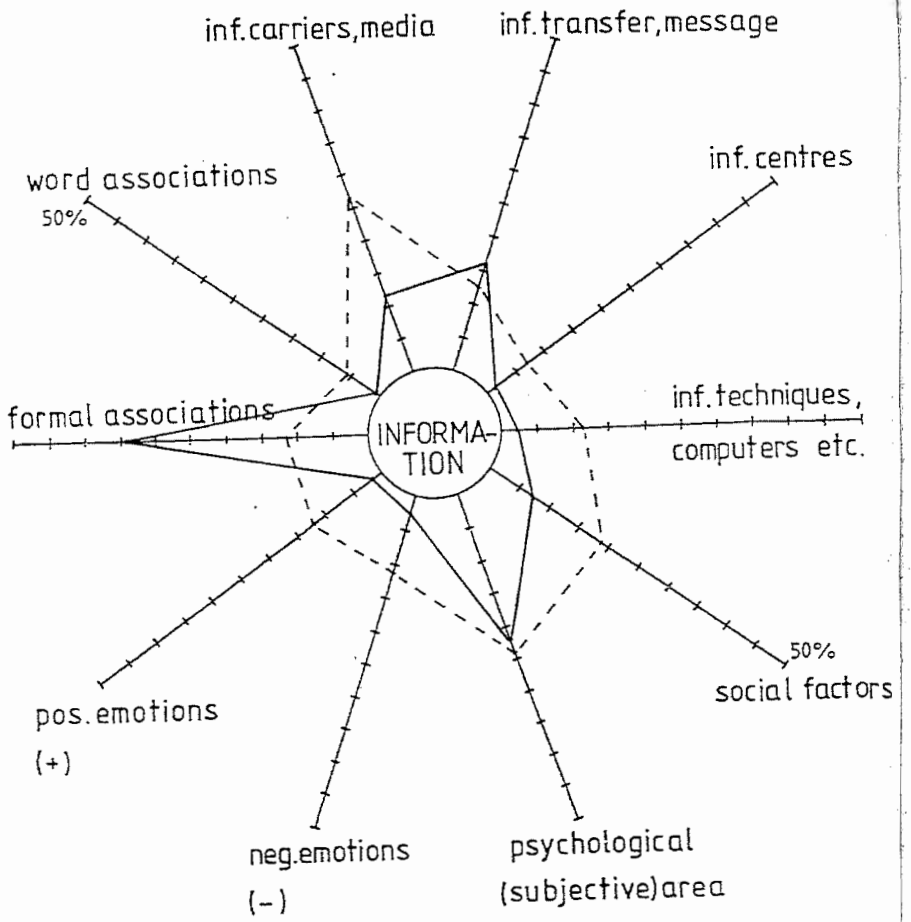

Figure 7. Total association profile (dotted line) and definition profile (permanent line). Population as in Figure 2.

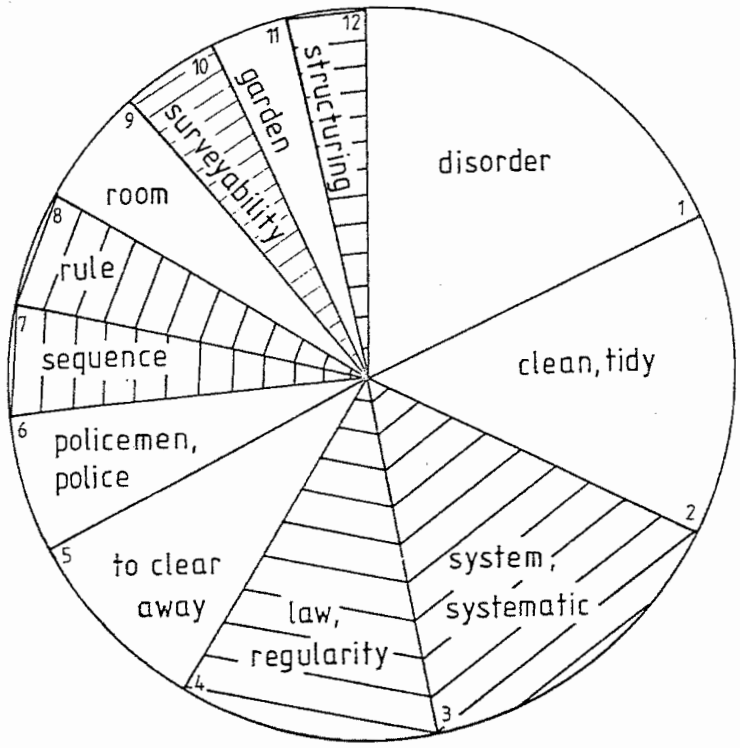

Figure 8. The 12 most frequent free associations to the key-word ORDER, in their relative distribution. Population as in Figure 2. Hatched areas: highly formal associations giving a good basis for a scientific understanding of the concept .

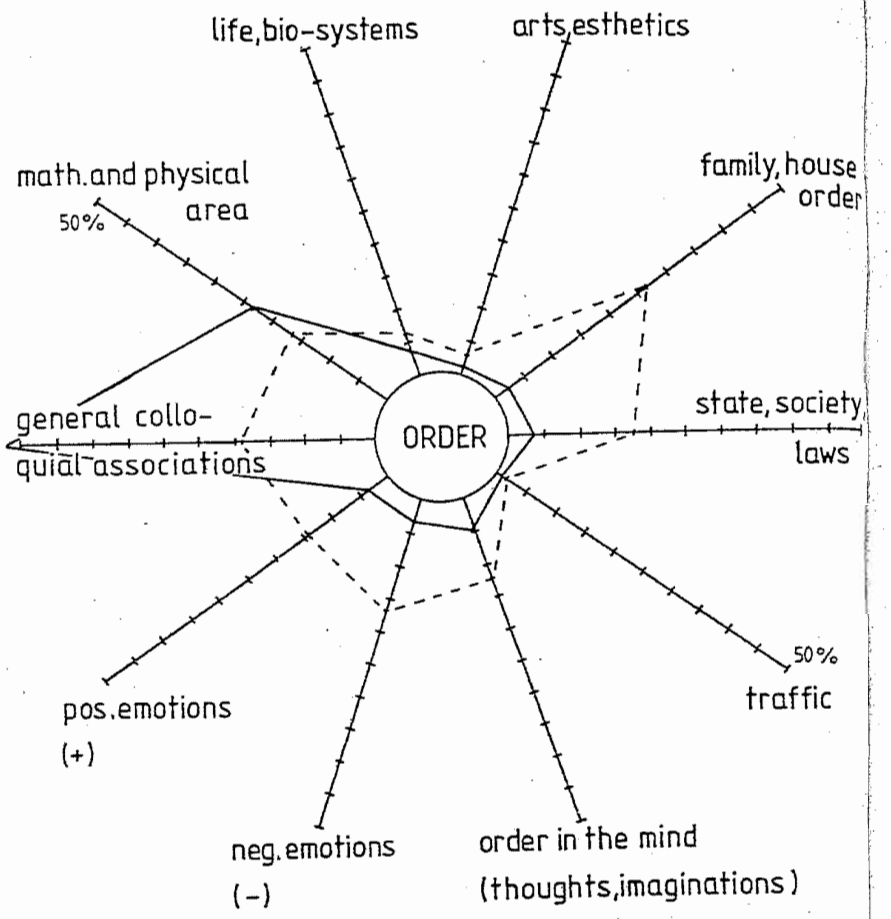

Figure 9. Total association profile (dotted line) and definition profile (permanent line). Population as in Figure 2.

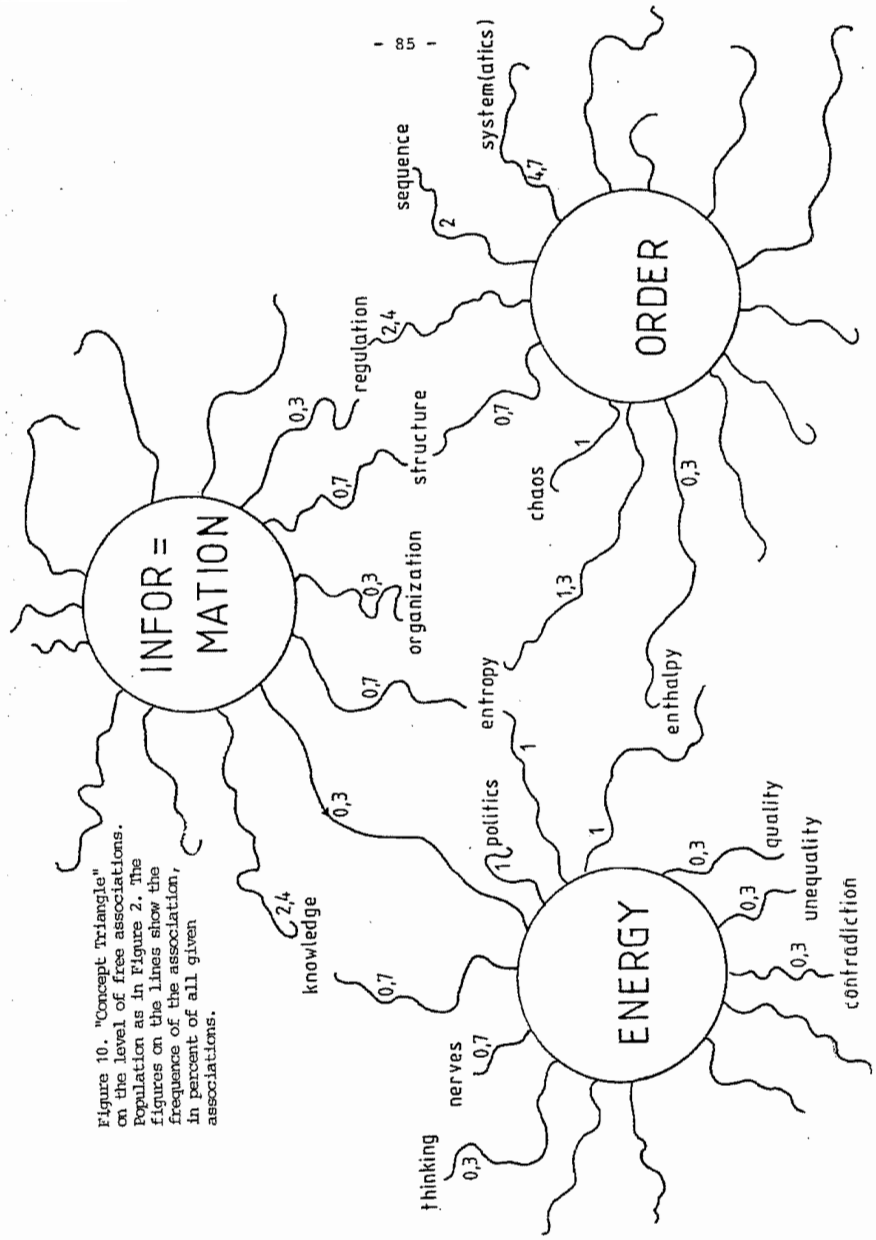

Figure 10. "Concept Triangle" on the level of free associations. Population as in Figure 2. The figures on the lines show the frequence of the association, in percent of all given associations.

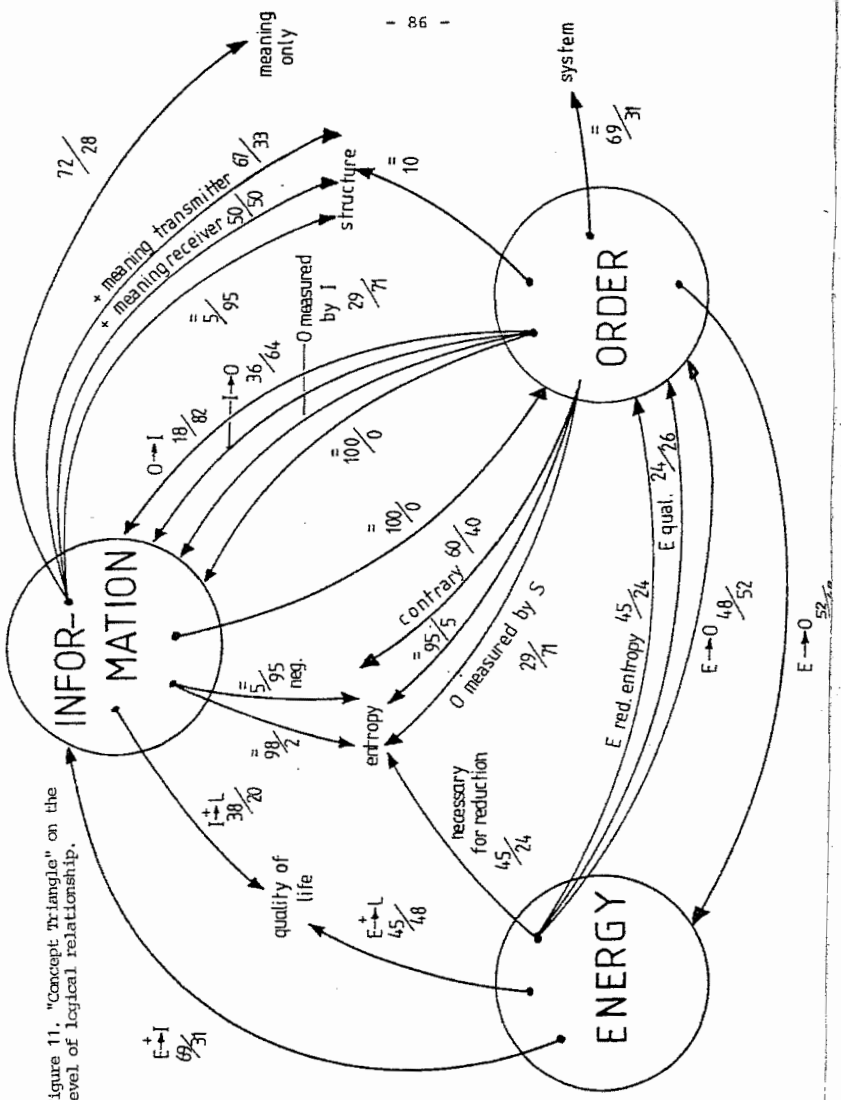

Figure 11. "Concept Triangle" on the level of logical relationship.

IS THE SECOND LAW OF THERMODYNAMICS EASIER TO UNDERSTAND THAN THE FIRST LAW?

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Am I posing a strange question in this paper? It seems so. Usually the first law comes first in physics instruction. The second law comes late. In many introductory physics courses for 10- to 15-year olds this law is completely disregarded. In the Federal Republic of Germany, for instance, the great majority of students leave school with almost no knowledge of the second law.

Is the second law too difficult a topic for most of the students? Or is an uneasy feeling among teachers and members of syllabus committees concerning the concept of entropy responsible for the minor role the second law plays in physics instruction?

The latter seems to be more likely. The following sections of this paper will present arguments to the effect that some aspects of the second law are easier to understand than others of the first law.

1. REMARKS ON THE HISTORICAL DEVELOPMENT

On the one hand, the second law may be regarded as older than the first law. Sadi Carnot worked out his famous theory of the steam engine in 1824. The second law was already contained in this theory. The idea of the first law arose about 20 years later in the work of a couple of researchers, predominantly independently of each other (Mayer, Helmholtz, Joule, Colding and others, see KUHN, 1959).

On the other hand, the first law may be taken as the older one. Roots of this law were already developed by Leibniz. The prin-

ciple of conservation of vis viva was already well known in the mechanics of the 18th century (see e.g. HIEBERT, 1962).

In connection with the question posed in this paper a short look at the development of the two laws in the 19th century could be of interest.
Ideas of the first law arose about 1842. The fathers of this law, namely Mayer, Joule, Helmholtz and Colding, did not infer it from empirical evidence. The contrary seems to be true. They were already convinced of the idea of (energy) conservation. This conviction was not only rooted in rational belief but in metaphysical or religious speculations too. This is also true for Joule. His empirical findings were so weak in the beginning of his work that only a person with a strong belief in the conservation idea could accept the results as empirical proof. In general, empirical evidence for the principle of energy conservation was still rather weak, even after it had been accepted by the scientific community (MEYERSON, 1930, 199 ff).[1]
The new idea of energy conservation was greeted with distrust by the physicists in the very beginning. The first papers of Mayer and Helmholtz, for instance, were rejected by the scientific community for several reasons. But it took only a short period of time for the principle of energy conservation to ascend to an unquestionable truth. By about 1860 the struggle for the acknowledgement of this principle was finished (PLANCK, 1913). In 1870, the principle was used in the discussion of Weber's theory of electrodynamics as proof of this theory (HELM, 1887, 47).

The second law had its origin in Sadi Carnot's theory of the steam engine. It was based on experiences with the transformation of heat into work. This law did not become part of

1 This statement refers to the general principle of energy conservation. The experiments on change of work to heat arrived at a quite sufficient standard of accuracy about 1850 already. But evidences for the validity of this principle in other areas still were rather weak.

physics until the first law had been accepted by some of the scientific community. Clausius formalized the second law in 1850 by introducing the concept of entropy. About 16 years later Boltzmann gave an interpretation of entropy in the particle model of statistical mechanics. Although the second law became one of the cornerstones of physics an uneasy feeling - especially with the concept of entropy - still remained.

There are several reasons for this.
Firstly, the mathematical form Clausius gave to the second law is considered as a source of misunderstandings (OSTWALD, 1908, 110). TRUESDELL (1980) voices the following accusation:

"Hitherto thermodynamics had been, like any other theory in mathematical physics, pretty, largely a model for the way things are. In Clausius hands it now begins to change into a model for the way things are not (337)."
"...thermodynamics turned its back on the real world (338)."

Secondly, the notion of conservation seems to be accepted much easier than the idea of irreversibility (see HELM, 1887, 53).[1] MEYERSON (1930) has dealt with this aspect in some detail. The pivot of Meyerson's philosophy is the idea that the search for identity in the midst of change is inherent in human thinking. Therefore, conservation principles are very "attractive" to the human mind. Human thinking has the tendency to look for something that does not change in time, something that can be reidentified.[2] There seems to be no such tendency for thinking within the framework of irreversibility.

1 My colleague G. Lind (IPN) mentioned an interesting reason when commenting on this paper. The first law was much more in accordance with the main philosophies among physicists of the 19th century than the second law. It met both ideas of romanticism and mechanistics. The second law was in contradiction to the idea of evolution inherent in some way in both mentioned philosophies. This idea starts from the principle that there is a progression in the world. The second law seemed to point out that on the contrary there is a retrogression.

2 The search for a constant amidst change is an old problem of philosophy. Concepts we use to recognize and structure our environment always point out in some way an invariance, an invariance in time of a material or quasi-material something or a structural invariance (SACHSSE, 1967; WEYL, 1966).

MEYERSON (1930, 272) points out, that the second law is presupposed implicitly at the beginning of most textbooks on heat. Poincaré's definition of temperature (the temperature of two bodies is the same, if neither expands when brought into contact), for instance, already makes use of the second law. Therefore, the second law seems to be a self-evident idea whenever dealing with heat phenomena. Meyerson points out further that the principle of the conservation of substance (material), the principle of inertia and the principle of energy conservation are in contradiction with everyday experiences much more than the common experience that heat travels only from hot to cold.

Meyersons' point of view may be summarized as follows. The second law stems from experiences with heat phenomena. It is implicitly presupposed whenever dealing with such phenomena and it is much more in accordance with everyday experiences than the first law.
The first law has its origin mainly in the tendency of human thinking to look for constancy amidst change. It is, therefore, more "attractive" for the human mind than the second law.

It may be interesting to mention that J. PIAGET (1973, 205) gave a very similar interpretation of the difference between the first and the second law. From the standpoint of his genetic epistemology the main difference is the following. The first law was postulated by rational belief before it could be accomodated to experiences. The second law was revealed by experiences before it could be assimilated to rational thinking.

2. EMPIRICAL STUDIES ON UNDERSTANDING THE FIRST AND SECOND LAWS

Lessons learned from the history of science may provide us with some ideas and hypotheses about learning difficulties in physics instruction. But if we want to get information

about learning the first and second laws by our students in school, empirical research is needed.
Unfortunately, only a small number of empirical studies is available in this area. This is true especially for studies concerning the second law.
The purpose of the following section is, therefore, twofold. On the one hand, I wish to present an overview on the body of knowledge available (as far as I know of it, of course). On the other hand I wish to mention areas where research seems to be necessary.

2.1. Empirical Studies Concerning the First Law

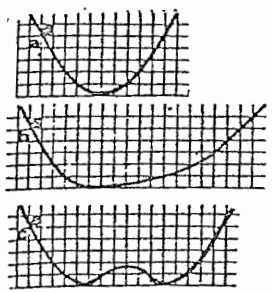
The formation of notions of conservation during cognitive development has been investigated by Jean Piaget and his co-workers in Geneva as well as by many "Piagetian researchers" all over the world.

According to genetic epistemology, the following three logical operations lead to conservation ideas: identity, reversibility and compensation (PIAGET, 1973, 125). The idea of conservation of substance (material) can already be found among 7 to 8 year olds. The idea of the conservation of weight follows about two years later, conservation of volume about a further two years later. The roots of "conservation ideas", therefore, crop up early in cognitive development. But the logical operations are applicable only to rather simple cases. They also cause severe difficulties for much older students (see e.g. LOVELL, 1966).

There is only a small number of studies within Piagetian research which deal with the conservation of energy (PIAGET, de LANNOY, 1973; DAHNCKE, 1973; JENELTEN-ALLKOFER, 1979). Explaining simple processes of mechanics (e.g. the coupled pendulum or the frictionless motion of bodies) even older students (about 16 years old) only seldom employed a type of thinking we would call thinking within the framework of

energy conservation. It seems that an idea of energy conservation which is applicable to processes in mechanics is not formed during cognitive development.

It is precisely these processes of mechanics that play an important role in many paths to the energy concept in school. Normally, the principle of energy conservation is not simply introduced as an axiom. Many empirical evidence is compiled to convince the students that this principle is true (see e.g. PS II 1969; ROGERS, 1965, 1971; IPN, 1978). Processes of mechanics are prefered for this purpose because the same state (e.g. the same height or the same speed) is present at the beginning and the end of a period of observation. Such teaching efforts seem not to be very successful. Empirical studies point out that only a minority of students in grades 6 to 10 employs the principle of energy conservation when explaining such mechanical processes. The majority of students prefers notions stemming from everyday experiences and words from everyday language. This is true even for students who have had some years of physics instruction in which the principle of energy conservation was given considerable attention (see JUNG et al., 1977; DUIT, 1981a, 1981b, 1983; DUIT, TALISAYON, 1981).
I would like to give one example for the mentioned learning problems of students in some more detail (see fig. 1).
The number of students who predict the correct height of the ball on paths b and c is substantially smaller than on path a. The word "energy" is used only by a minority of students when explaining the prediction. Most students use words from their everyday language like swing (Schwung).
A rather small number of students argues with the principle of energy conservation. Most explanations follow notions and ideas stemming from everyday experiences or mention geometrical qualities of the paths (e.g. the symmetry of path a).



The ball is released at the marked spot and rolls with no drive of its own. We will pretend that there is no friction.

	a	b	c
Prediction of correct height	47	26	33
Use of energy for explanation	35	26	22
Use of energy conservation for explanation	26	18	15

171 students, grade 10, after physics instruction in grades 7 to 10

fig. 1: The motion of a ball in curved paths.
Figures give percentages.
The idea for this task stems from DAHNCKE (1973).

In a study on misconceptions in school thermodynamics (JOHNSTONE, MACDONALD, WEBB, 1977) more than half of about 100 students in the sixth form were not able to understand that the amount of heat produced during a chemical reaction decreases when the amount of work increases.

I think it is allowed to summarize that comprehending the first law of thermodynamics is not at all an easy task for students in school physics teaching.
This statement contradicts the way the aspect of energy conservation is handled in some proposals for teaching energy. FALK/HERRMANN (1979) and SCHLICHTING/BACKHAUS (1979) think that energy conservation is more or less self-evident for students even of grades 5 to 10. They conceptualize energy as a quasi material substance. They deal with energy conservation, but don't mention this aspect. It may be that within such "materialist" conceptualisation, energy conservation is accepted more easily by students than in other approaches. But there are no empirical studies until now, which give information concerning whether this is indeed so.

2.2. Empirical Studies Concerning the Second Law

Only very little information is available concerning the learning of the second law. Studies on heat (e.g. ERICKSON, 1979) reveal almost nothing about notions of the second law.

In the study of JOHNSTON, MACDONALD and WEBB (1977) already mentioned above, we find some results which might be of interest here. Most of the students, for instance, think that entropy is a measure of disorder. But in general the knowledge about entropy is superficial. There is also a tendency to mix up entropy and kinetic energy.

Within the work of Piaget and his co-workers we find studies on the formation of the idea of chance (PIAGET, 1973, 1975). The development of this idea as precondition of understanding irreversibility is closely affiliated with the development of the operation of reversibility. When this operation becomes a workable tool for children (beginning at the age level of about 7 to 8 years), first ideas of chance arise too. In much the same way as the operation of reversibility becomes more formal during cognitive development, the idea of chance becomes more formal, too.

Is the idea of energy degradation (in which the central ideas of the second law are included) contained in the everyday meaning of energy?
Some researchers think that it is so (SCHLICHTING/BACKHAUS, 1980; OGBORN, 1981; SOLOMON, 1982). Words like "energy consumption" or "useless energy" are given as reference. But there are no empirical studies which give information, whether this is indeed so. My own studies on the meaning of the word energy in German everyday language gave no hints that the idea of energy degradation is contained within the meaning of energy among a significant number of students (DUIT, 1983). But it may well be that the methods (e.g. association tests, definitions and examples for energy) employed in my studies for investigating meaning are too limited to get to know

something about aspects of energy degradation.

2.3. Concluding Remarks Concerning Empirical Findings

We don't know much about learning the first law and we know almost nothing about learning the second law.

What we know about learning energy conservation (the first law) reveals severe difficulties on the part of the students to make use of the principle. This is true even for explaining processes of mechanics which have been used in instruction to convince the students that this principle is valid. To understand the principle of energy conservation in a way which goes beyond a mainly qualitative feeling (nothing comes from nothing and goes into nothing) is not as easy as one could have expected, going by the historical development (see 1.).

3. SUMMARY AND SOME RECOMMENDATIONS

I hope that the preceding sections have explained why the question posed in this paper is not a strange one. But it is not easy to give a comprehensive answer. What can be said is the following. The first law is not as easy as one could expect, taking the major role of this principle even in introductory physics courses for grades 5 to 10 into consideration.
There is reason to believe that the minor role the second law plays in school physics teaching is caused mainly by prejudices of people with an uneasy feeling about the entropy concept. The second law seems to be much more in accordance with everyday experiences. Furthermore, whenever we deal with heat in school the second law is implicitly presupposed.

In recent years the number of researchers who are free from the uneasy feeling with regard to the entropy concept and the second law is increasing. There are already proposals to

teach aspects of the second law in a mainly qualitative way from the very beginning in school physics instruction (see e.g. SCHLICHTING, BACKHAUS, 1980; SOLOMON, 1982; "lesson dreams" of OGBORN, 1981; DUIT, HÄUSSLER, 1983).

I want to conclude this paper with the following statement. There is no doubt that we need further proposals for dealing with energy conservation and degradation in school. But it seems to be more urgent at the moment to carry out empirical studies on learning these pivotal aspects of the energy concept. I will try to continue in such research work. I would be glad to share results with other researchers.

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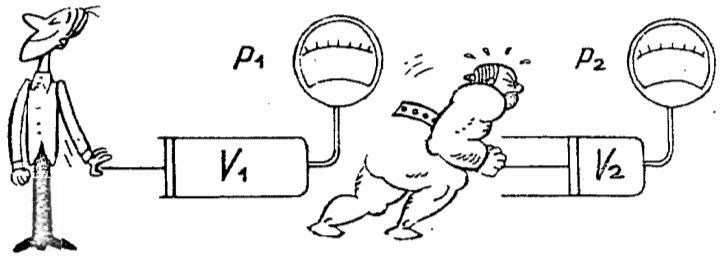

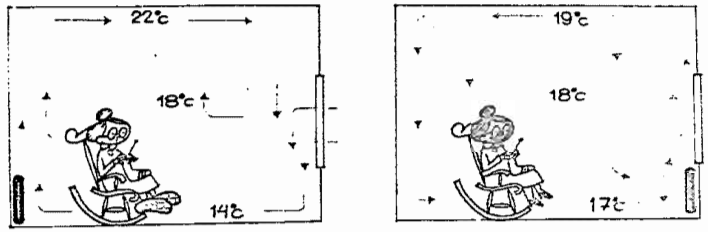

Kumpi on parempi lämpöpatterin sijoituspaikka, ikkunan alusta vai takaseinä?

from "Ylaasteen fysiikka ja kemia" for grade 7-9
by Harma, Nurmi, Tiilikainen, Helsinki

BACKGROUND

THE SECOND LAW OF THERMODYNAMICS HOLDS, I THINK, THE SUPREME POSITION AMONG THE LAWS OF NATURE.

Sir Arthur Eddington

ALL SPECIES DEPEND ON THE SUN AS THEIR SOURCE OF LOW ENTROPY EXCEPT THE HUMAN RACE, WHICH HAS LEARNED TO EXPLOIT THE TERRESTRIAL STORES OF LOW ENTROPY SUCH AS FOSSIL FUELS AND METALS.

N. Georgescu-Rogen

ENTROPY IS THE MOST ANTHROPOMORPHIC CONCEPT IN SCIENCE.

E.P. Wigner

from "Ordnung und Chaos" by R.U. Sexl

WHAT YOU ALWAYS WANTED TO KNOW ABOUT ENTROPY AND NEVER DARED TO ASK

Roman U. Sexl
Institut für theoretische Physik der Universität Wien

1. Introduction

For many people entropy seems to be one of the most mysterious quantities known to natural science. Hardly any physicists working outside of thermodynamics is able to give any meaningful estimate of the entropy of some objects - a glass of water, a stone or a piece of metal. The same physicist usually does have some feeling for the energy involved in heating the glass of water, in throwing the stone or in melting the metal.

Why is entropy much more mysterious than energy?

One of the reasons might be that it is not a conserved quantity. It does not behave like a substance, the motion of flow of which you can follow through space. Entropy can be created and is continously being created almost everywhere.

Another reason is probably that school physics was never really able to find any non-trivial applications of the entropy concept. While many problems dealing with energy exist and are a standard part of the physics curriculum, this is not the case with entropy. Almost all problems involving entropy could also be dealt with without the use of this concept. That heat flows from a hot body to a cold one can be derived e.g. by calculating the corresponding increase in entropy - the result is however neither surprising nor interesting.

The problem of introducing the entropy concept into schools is therefore a twofold one:

Firstly a convincing and simple way has to be found

for the introduction of this concept into the curriculum.

Secondly a number of interesting and motivating examples have to be found where non-trivial results can be obtained with the help of the new concept.

Since it seems to be so hard to use the entropy concept at all within school physics one might ask why bother to introduce it at all. Couldn't physics get along without entropy?

Our answer to this is that physics teaching in school probably could get along without entropy. An introduction of the Carnot efficiencies and their importance for thermodynamic machines would certainly be sufficient for a general education in physics. Physics is, however, not the only science tought in school. Chemistry - and increasingly also biology - does need the entropy concept. Handling entropy tables is one of the teaching aims there.

School physics does not need entropy - the pupils does. We shall sketch in this first part of our paper an information theory approach to entropy. It has the advantage of mathematical simplicity and of providing many fascinating applications.

In the second part of the paper - presented by Alfred Pflug - novel applications of the entropy concepts will be given. Bridging the gap between physics, chemistry and biology is our aim there.

Laplace's Daimon
- with crystall ball
and computer

2. The Unit of Information

A unit of information is needed, in order to make information a metrical concept. This unit is the bit. It corresponds to the information contained in the answer to a question such as: "Up or down?"; "Yes or no?"; "To be or not to be?". One bit of information allows one to distinguish between two possibilities, which can be symbolized e.g. by the numbers 0 and 1.

Two bits of information allow one to distinguish between four possibilites, three bits contain the information which of eight possible events occurs (Fig. 1).

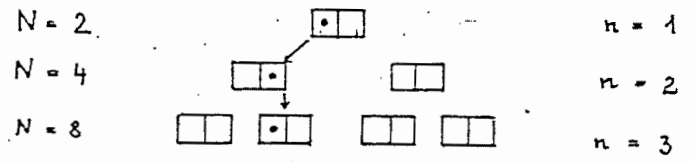

Fig. 1 - Information needed to distinguish between N possible cases

The general result is:

> n bit of information are required to distinguish between $N = 2^n$ events.

This relation can also be written in the form

$$n = \log_2 N = \log N / \log 2 \quad . \qquad (1)$$

3. Examples From Various Sciences

Let us first consider several examples of information storage. The table gives the number of bits contained in various sources of information. (In deriving it we have assumed e.g. that all letters of the alphabet occur with equal probability. Only in this case our simple result (1) can be applied. If this is not the case - or if the sequence of letters contains correlations - the amount of information contained in one letter is less than the result indicated above. This leads to interesting questions of redundancy, which will not be dealt with here.)

Table 1

Alphabet	N = 32	n = 5
Genetic Code	N = 4	n = 2
Numbers	N = 10	n = 3,32

This simple table already permits us to answer some interesting questions. Let us start with an example from biology. The double helix of Drosophila, containing its genetic code, is a giant molecule with a length L = 1,2 cm. Each of its subunits which contains 2 bits of information has a length of approximately $\ell = 1{,}2.10^{-7}$ cm. Thus the total information contained in the genetic code of drosophila is

$$n = L/\ell = 2.10^7 \text{ bit} . \qquad (2)$$

In a similar way one derives the information contents of various organisms as shown in table 2. With the help of table 1 we can translate this now into various other types of information. How many pages are needed for a "build-your-own-man-book"? If one page has 30 lines with 70 characters each its information contents is

$$n(1 \text{ page}) = 30 \times 70 \times 5 = 10^4 \text{ bit} . \qquad (3)$$

Table 2

Organism	Information
Virus	2.10^4 bit
Drosophila	2.10^7 bit
Man	10^9 bit

Therefore the instruction leaflet for building a virus has 2 pages, for Drosophila 2000 pages and for man 10^5 pages = 500 books. I always find it rather surprising how little information is needed to build a virus. Maybe this fact can help in understanding how life can have originated.

Another example for the transmission of information which leads to interesting results is the following: How long does it take to send a man to the moon in form of a telegram? Transmitting at a rate 50 bit/s (which corresponds to 10 characters per second) the telegram would take about eight months to send, as one easily sees.

This results brings us to one of the most important technical problems in communication theory. If we want to communicate information at a great rate - as is required in our present society - one has to switch currents off and on as fast as possible. In each half wave of an alternating current one bit of information can be stored (half wave at full amplitude or not). Therefore the feasibility of communication networks was linked historically to the progress of high frequency technology. The highest requirements are posed by television. Each TV-picture consists of 500 lines containing 600 points each, i.e. a total of 3.10^5 points. If we assume for simplicity that each point can be either black or white, the total information contents of one picture becomes 3.10^5 bit. Since 25 pictures have to be transmitted per second the total information flow becomes $7{,}5.10^6$ bit/s. From this we can easily calculate the band width required for the transmission of TV-pictures. Since each bit corresponds to a half wave the total band width becomes

$$\Delta f = \frac{1}{2} \cdot 7{,}5.10^6/s = 4 \text{ MHz} . \qquad (4)$$

The frequency f of the carrier signal should be at least $f \approx 10\ \Delta f \approx$ ≈ 40 MHz. From the relation $f.\lambda = c$ we can calculate now the wavelength used for the television purposes:

$$\lambda = c/f = 3.10^8 \text{ m}/4.10^7 \text{ s}^{-1} \approx 10 \text{ m} \quad . \tag{5}$$

Returning to our examples from biology we can calculate now to how many seconds of TV-commercials the genetic information contained in man corresponds. Since roughly 10^7 bit/s can be transmitted we obtain for the time T needed:

$$10^7 \text{ bit/s} \ . \ T = 10^9 \text{ bit} \quad \text{or} \quad T = 100 \text{ s} \quad . \tag{6}$$

Therefore it would take about two minutes to transform man in form of a TV-commercial.

In another example using television we can check the proverb: "Ein Bild sagt mehr als 1000 Worte" (a picture says more than a thousand words). One word contains about 30 bit of information, if we assume that it consists of six letters. Therefore the information contained in 1000 words is 3.10^4 bit. On the other hand we calculated before that one television picture contains about 3.10^5 bit. Therefore one picture corresponds to roughly 10.000 words (or about 30 pages).

In conclusion we want to mention another problem which can also be solved with the help of information theory. Given are 12 balls, one of which is either heavier or lighter than the other balls. One has to find out with the help of a balance which of the balls deviates from the others and whether it is heavier or lighter. The problem is clearly one of missing information, which is to be gained with a balance. How often do we have to weigh the balls in order to gain the missing information?

4. Entropy and Information

One of the most interesting - and also one of the earliest - uses of the information theory is the entropy concept. Its connection with information can be characterized as follows:

In mechanics one assumes that the positions and velocities of all particles composing a system are known initially. In thermodynamics no such knowledge about the individual positions and velocities of the molecules in a gas is possible or desirable. This lack of information about the thermodynamic system is described by the concept of entropy.

As an example we consider the expansion of a gas into a vacuum (Fig. 2).

Fig. 2 - Expansion of a gas in a vacuum

When a gas expands into vacuum information is lost. Before the expansion we were able to answer the question: Left or right? for each molecule. After the expansion this is no longer possible. Therefore a loss of information occurs, which amounts to $\Delta \bar{I} = N$ bit, if the gas is composed of N molecules. We define the increase of entropy during this process by

$$\Delta S = (k \ln 2)\ \Delta \bar{I} \quad , \tag{7}$$

where k is Boltzmann's constant. The factor of proportionality in (7) is chosen in such a way that the proper conversion from information units

to thermodynamic units is achieved.

In order to show that (7) is the proper definition of entropy (increase) we have to demonstrate that the standard relation $\Delta S \geq Q/T$ is fulfilled. This can be done rather easily in one example, i.e. by comparing the irreversible expansion into the vacuum (Figure 2) with the reversible expansion of the same gas. If the gas is not isolated but in contact with a heat reservoir the temperature will remain constant during the expansion process. Therefore both the reversible and the irreversible expansion lead to the same final state of the gas.

The difference between these two processes is, however, the during the irreversible expansion the gas is isolated, while it absorbes an amount Q of heat from the reservoir, which has to be equal to the work performed by the gas on the moving piston. This work can easily be calculated to be

$$W = (\ln 2)\, p\, V .$$

where the factor $\ln 2 = .69$ takes into account that the pressure of the gas decreases during the expansion process. Using $pV = NkT$ and $W = Q$ we obtain

$$Q = k(\ln 2)\, N\, T = \Delta S\, T$$

Thereby we have bridged the gap between the information theory approach to entropy and the standard one.

More examples can be used to make the the student more familiar with the new concepts introduced here. A simple problem is e.g. the mixing entropy. If two equal amounts of gas A and B are mixed, what is the increase in entropy during this irreversible process?

The standard expression for the entropy of an ideal gas

$$S = N\, k \ln V + \frac{3}{2} N\, k \ln T + \text{const.} \qquad (8)$$

where? how fast?

can be interpreted without difficulty from the point of view of information theory: The first term contains the lack of information about the exact position of the molecules, the second term contains the lack of information on the exact velocities (or momenta) of the molecules. For a hot gas the Maxwell distribution of the velocities of the molecules will be very broad and little information will be available on the velocities of the individual molecules.

From here it is easy to see why quantum mechanics came out of thermodynamics: If we put $V = (\Delta x)^3$ and use the relation $p^2 \propto (\Delta p)^2 \propto T$ for the momentum spread of the gas molecules we have

$$S = N\, k \ln(\Delta x)^3 + \frac{3}{2} N\, k \ln(\Delta p)^2 + \text{const} = 3\, N\, k \ln(\Delta x\, \Delta p) + \text{const.} \qquad (9)$$

In classical physics there was no appropriate constant which could be used to make the argument of the logarithm a pure number. In fact, the lack of information about the thermodynamic system is always infinite in classical physics, since all momenta and positions should be known with infinite accuracy. Quantum mechanics showed how to make this logarithm dimensionless:

$$S = 3\, N\, k \ln\left(\frac{\Delta x\, \Delta p}{h}\right) , \qquad (10)$$

by introducing a limit to the accuracy of measurability. It is therefore no accident that Planck's constant and the first hints towards the quantum theory came out of thermodynamics.

5. From entropy to free enthalpy

Hardly any physicist, chemist or biologist I know, works in a vacuum. A theorem involving isolated systems only is therefore of little use of them. The systems considered are usually in some contact with their environment, exchanging energy in the form of heat or work in order to maintain the constant temperature or pressure, or both, imposed by their surroundings.

Systems plus surroundings form a closed system, however, and to this system we can apply the second law of thermodynamics in its standard form: The entropy S of the total system increases, while its energy E remains constant. This statement does not appear to be very helpful, since we are interested in a prediction about the behaviour of the system and not a theorem involving also its surroundings - including students, laboratory assistants and other equipment.

The solution of this difficulty is well known and can be found in any textbook of thermodynamics: The statement that the entropy of the total system increases can be converted into a statement about the system alone by taking energy conservation into account.

The result is that the free energy $F = U - TS$ of the system is minimal if only heat is exchanged with the environment, while the Gibbs potential $G = F + pV$ is minimal if also work can be exchanged.

With the introduction of these two new quantities we have the formal tools at hand for dealing with a number of most interesting applications of thermodynamics to physics, chemistry and biology, which will be dealt with in the second part of this paper.

THERMODYNAMICS OF THE UNIVERSE

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When I talked about the increase of disorder on Rubik's cube, the pupils started asking me about the real world. "Who made order in the universe at the beginning?" - "How free energy has been created?" - and so on. These are century old problems in the thermodynamics, answered only by recent research. I think it may be useful for a teacher to know the answer to these simple and deep questions even if the argumentation will not be incorporated into conventional school textbooks in the forseeable future.

The Newtonian Dilemma

The success of the Newtonian program is due to the fact, that the equations of motion have been formulated in form of time dependent differential equations.

$$\frac{dX}{dt} = F(X), \qquad (1)$$

based on laboratory observations. (Here X is the set of parameters characterizing the state of the material system, e.g. the set of coordinate and velocity values.) But in order to get X(t), to explain the present state of the world, beside the differential equations (1) one needs also to know the initial conditions.

$$X(0) = X_0. \qquad (2)$$

But these cannot be learned by experimenting in laboratories!

One tried to borrow them from elsewhere (from theology or philosophy). Scientists of the last century were worried about this alien element in science. To be able to explain the material world by itself, they tried to postulate a steady state for the universe, at least on large scale:

$$\frac{dX}{dt} = 0.$$

On this way they hoped to be able to deduce the specific steady state X_0 of the actual universe by solving the time independent equation

$$F(X_0) = 0.$$

Theoretical investigations have shown, however that this static (geometric) world picture contains inherent logical difficulties which were expressed by three famous paradoxa of the history of science at the end of the 109th century.

OLBERS PARADOXON: If a star of luminosity (light power) P is at a distance r, it produces a light intensity $I_0(r) = P/4\pi r^2$ at the Earth. If such stars are distributed uniformly in space with an (average) density n, they produce an integrated light intensity

$$I = \int_{r_{min}}^{\infty} I_0(r)\, n\, 4\pi r^2 dr = Pn \int_{r_{min}}^{\infty} dr = \infty$$

THE UNIVERSE COULD BE THE ULTIMATE FREE LUNCH.

M. Turner

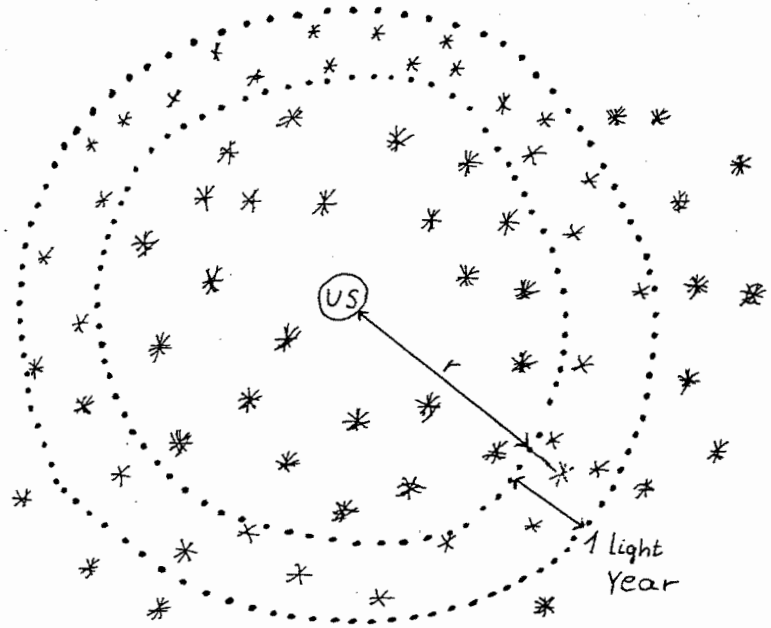


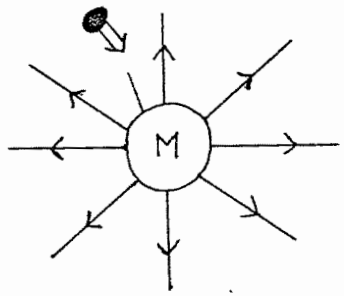
Figure 1.

at the Earth. This is in contradiction with the observation that it is dark at night.

CLAUSIUS PARADOXON: A universe with a steady (average) mass density will reach its state of maximum entropy density in a finite time. (More exactly: it will approach the state of thermal equilibrium with an arbitrary accuracy in a finite time.) So an infinitely old static universe must be already in the state of "heat death". This is in contradiction with the fact, that we experience light and dark, hot and cold in our universe.

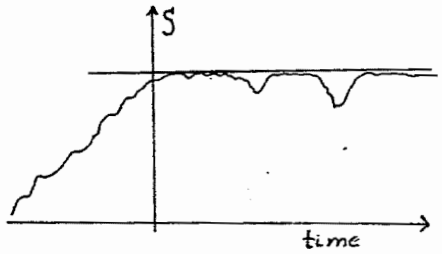
SEELIGER PARADOXON: The classical equation of the gravitational potential

$$\nabla^2\phi = 4\pi G\varrho$$



has a homogenous solution ϕ only in the case $\varrho = 0$. Expressed on a more picturesque way: any mass M is the source of $4\pi GM$ gravitational lines of force. All masses M are positive, so these lines do not chancel. If, however, gravitational force is present in space, the masses accelerate along these lines, excluding a steady distribution. This is a sophisticated way to formulate the simple observation, that a stone cannot float still near to a large body. It must accelerate toward the large body: it falls into, it orbits around or runs away from the other body. Only an empty universe can be in a steady state.

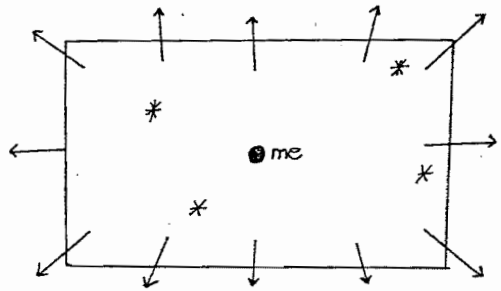
The paradoxa originating from the scientific belief in a timeless universe produced a lot of headache at the turn of the century. Boltzmann tried to argue that the present state of low entropy is just a transient fluctuation. Einstein was willing to correct the empirical equations of motion in order to secure a sensible steady solution, to satisfy its philosophycal credo.



Big Bang

A shock treatment by history helped to break through the mental barrier (Petrograd, 1922). Alex Fridman was the first to conclude from the physical equations of motion, that our world cannot be and is not static. It must be either contracting or expanding. A technological revolution (California, 1929), the installation of the 100 inch telescope at Mount Wilson confirmed the expansion of the Universe. A general red shift was observed by Edwin Hubble in the spectra of galaxies, indicating that the galaxies were running away, each galaxy from any other. The material universe is in the state of general expansion, the runaway speed being proportional to the distance:

$$v = H^{-1}r. \qquad (3)$$



PAST AND FUTURE ARE SO MARKEDLY DIFFERENT BECAUSE THE UNIVERSE IS STILL VERY YOUNG.

F.Hund

The present value of the Hubble proportionality factor is

$$H^{-1} = \frac{15 \pm 3 \text{ km s}^{-1}}{\text{million light years}} . \qquad (4)$$

Hubble's law (3) has a simple interpretation. Let us imagine a strudel sheet (or the rubber sheet of a baby). If one stretches the sheet uniformly, its length R(t) increases and the distance between any two (dust) grains r(t) increases proportional to R(t).

Hubble's Law (3) has a simple interpretation. Let us write it in the form

$$r = v \cdot H .$$

The higher is the speed of the galaxy, the higher will be its distance. This can be understood, if H is the time passed since the starting of runaway. Using the empirical value (4) one gets H = 24 billion years. But the galaxies attract each other, so the runaway decelerates. The speed of expansion was larger in the past, so the actual age of the Universe must be smaller than H:

$$t < 24 \text{ billion years.}$$

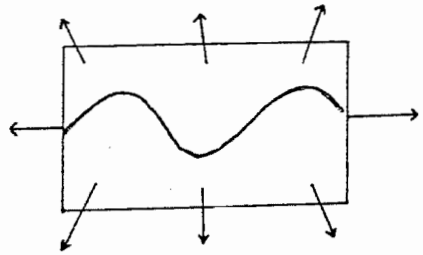
(It may be about 16 billion years.) The Beginning has got the nickname Big Bang.

Hot Universe

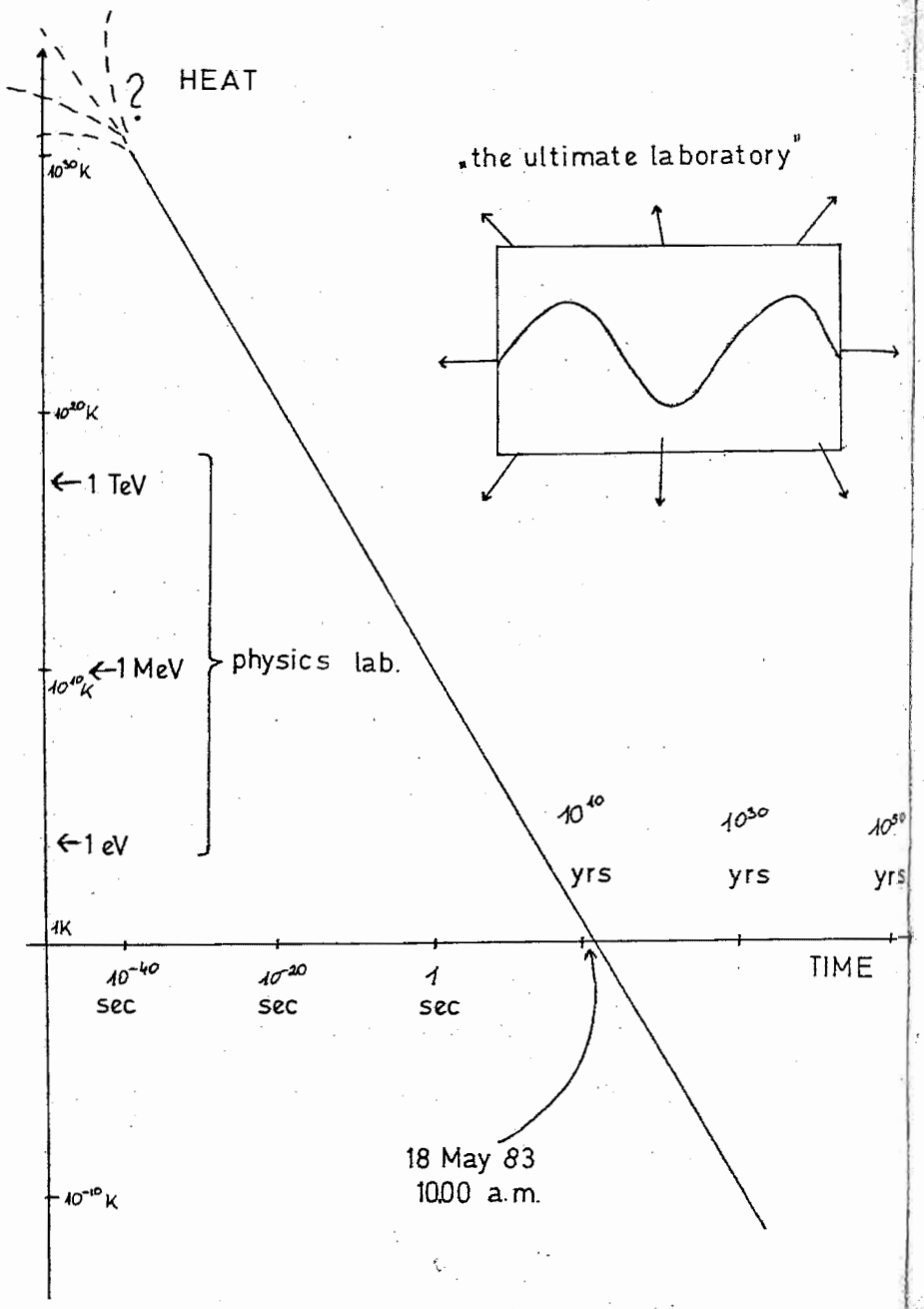
Abbot Lemaitre (at the Catholic University of Louvain in 1934, when radioactivity was a fresh field of research) described the start of the runaway as the radioactive decay of a "primordial atom". (Present day scientists would speak about the explosion of a bomb or about a phase transition, indicating that an important change had happened in the state of cosmic matter.)

In the thirties our knowledge was too poor to understand such detailes. In 1948 George Gamow (who moved from Petrograd to Washington in the meantime) started using nuclear physics in his efficient argumentation. If the early universe was very dense, all the nuclear particles were compressed, consequently today one would expect a high abundance of the (most stable) heavy elements. But the present universe is made of the lightest elements (hydrogen and helium in 99.9 per cent)! The only explanation could be, argued Gamow, that the early dense Universe had been very hot, preventing the formation of composite nuclei.

Two radio engineers of the Bell Telephon Laboratory were scanning the sky for low noise band in the early era of satellite telecommunication (1964). On this way Penzias and Wilson discovered, that space was filled isotropically with an electromagnetic noise, corresponding to T = 2.7 K radiation temperature. The present wave length values are in the cm region, but earlier it was not so. An electromagnetic wave is a sine curve drawn on a (strudel or rubber)

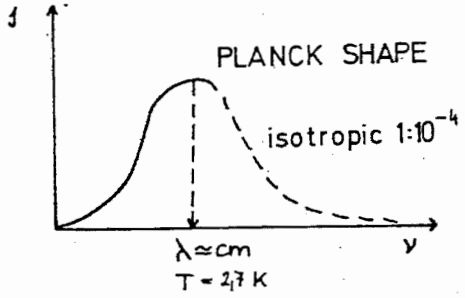


sheet. If the sheet of the size R(t) is stretched, λ will grow and T will drop, in accordance with Wien's displacement law (λ T = fixed). When the distances were thousand times smaller, the temperature was thousand times higher (above the ionisation temperature of atoms). When the distances were billion times smaller, the temperature was billion times higher (above the dissotiation temperature of nuclei). On this way the thermal history can be reconstructed.



In the Universe there are billion times more photons than atoms. The Universe is crowded by light.

In the year 100 000 after Big Bang the cosmic temperature T dropped below 1000 degrees, the energy kT of thermal motion dropped below 1 eV. This was smaller than the ionisation energy of the hydrogen atom. The protons captured the colliding electrons: neutral hydrogen atoms were formed. The hydrogen gas could become transparent for electromagnetic radiation. The relic electromagnetic radiation, what we observe today, originates from this era. The spectrum of the observed radiation shows a Planck shape and it has the same intensity from any direction up to four decimals. This indicates that the world was in thermal equilibrium in the year 100 000 after Big Bang.



This empirical conclusion corresponds well to the theoretical expectation. Gravitational force is a universal property of all sorts of matter:

$$F = G \frac{M \cdot M}{r^2} .$$

When the temperature T was very high, all the particles possessed a large energy E = kT, which corresponded to a big mass $M = E/c^2$. These big masses acted at each other with a strong force F at small distances r. According to theoretical calculation the early hot and dense universe forgot about its peculiar initial state and established

a thermal equilibrium (maximum entropy) within 10^{-40}s. This thermal equilibrium is what we observe in the relic radiation. The universal radio noise is not the bliss of creation, but the glow of hell!

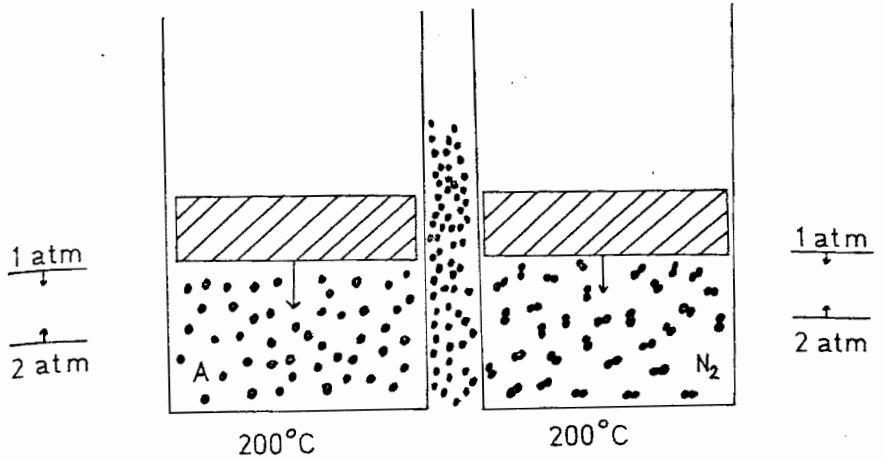
Today, more than 10^{10} years after Big Bang, we are not in the state of heat death any longer. We experience shade and light, cool and hot, death and life. The Universe experienced a resurrection from the heat death. How could it happen?

Resurrection from Heat Death

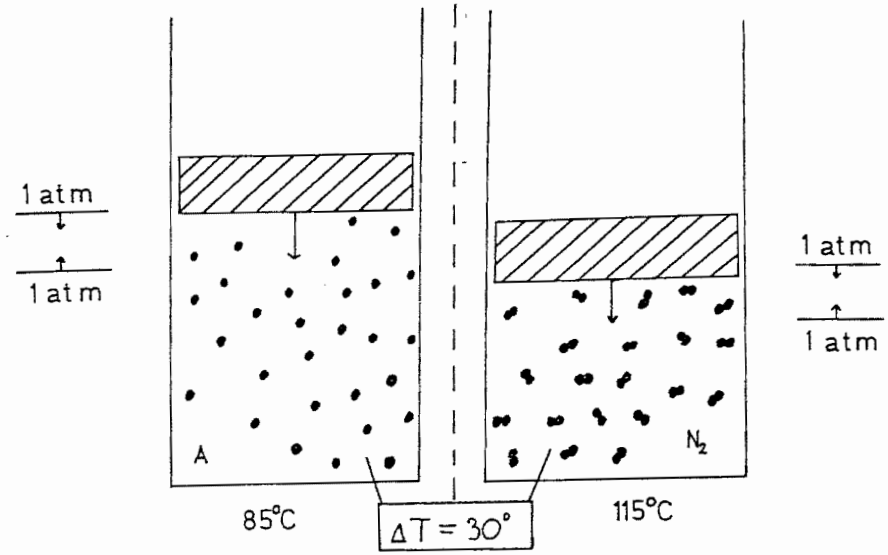
Let us consider a simple model example. Two containers are in thermal contact, consequently both are of equal temperature: 200°C. In the first container there is argon gas of 2 atm pressure, in the second container nitrogen gas of 2 atm pressure.

The piston acts with a pressure of 1 atm. Release the pistons! Both gases will expand quickly (adiabatically) from 2 to 1 atm pressure, independently of each other. Argon is a monoatomic gas; according to the adiabatic gas equation it will cool to 85°C. Nitrogen is a twoatomic gas, it will cool to 115°C. (Nitrogen molecules have also rotational degrees of freedom for energy storage, nitrogen gas has a larger heat capacity, so it can perform the same work at the expense of a smaller drop of temperature.)

From an isothermal state the adiabatic expansion against gravity produced a temperature difference of 30°. If one waits for a bit, the different temperatures will level up, producing a new thermal equilibrium (finally reaching a state with a higher value of the maximum entropy). But if we do not wait, we can exploit the transient entropy difference to perform useful work.



GAS PERFORMS WORK AT THE COST OF THERMAL MOTION



This laboratory example allowes us to formulate the following thesis:

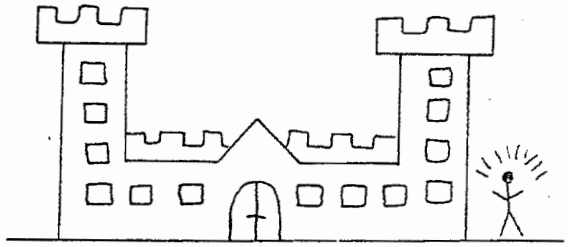
DYNAMICS: The equations of motion do not have static solutions, they contain an inherent instability.

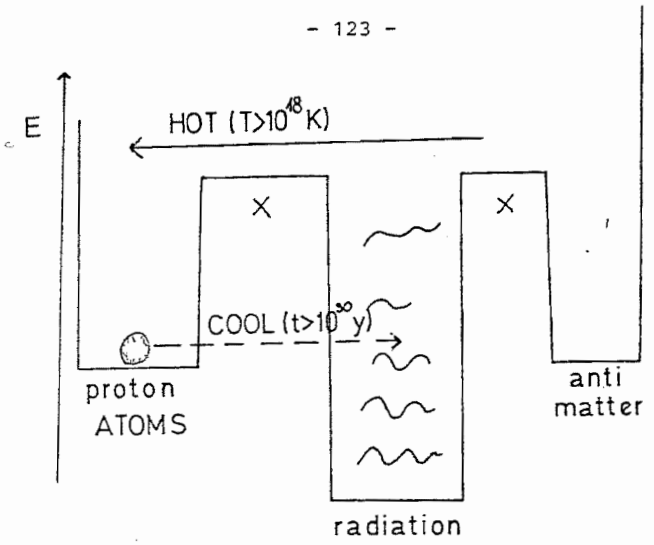
MATTER differentiated in early phase transitions, the different components - performing work against gravity - cooled with different speeds.

THERMODYNAMICS: Thermal differences tried to level up, collisions acted in the direction of equipartition of energy (Second Law). In the dynamicaly expanding universe, however, the interactions got weaker, density got thinner, so the collision time got longer than the actual age of the universe. On this way thermal differences were produced. From the G = 0 state of the black body radiation the fast expansion created free energy G > 0. Thus expansion reiuvenated the universe.

I used to explain this to my students with the following tale: Let us imagine a huge castle with many-many closed rooms. A naughty kid who can make complete disorder in any room in five minutes, enters the castle. A room is opened for him and he starts increasing the entropy immediately. But each minute the door of a few room is opened. The entropy keeps increasing, but the kid gets always farer from the complete disorder.

In principle this argument is easy to understand. The aim of contemporary research in astrophysics is to find out, how this works in details.



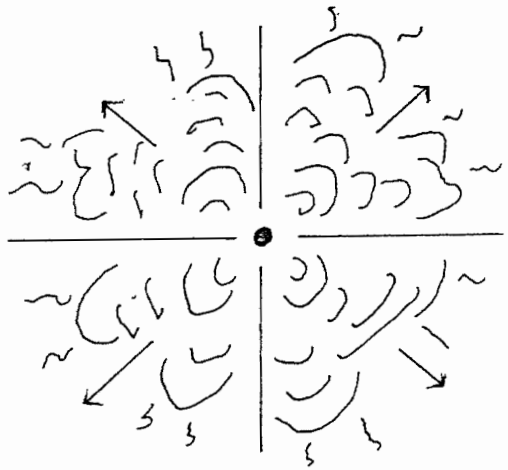


Mousetraps

MOUSETRAP NO 1: PROTONS VERSUS PHOTONS. A hydrogen atom has a lower entropy, than the radiation having a total energy of $M_H c^2 = 10^9$ electron volts. The transition

$$p^+ + e^- \rightarrow \text{radiation}$$

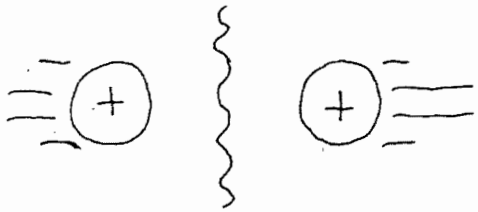
would be favoured thermodynamically. According to the fashionable Grand Unification Theories such transitions are allowed via the hypothetical X particle. How comes that there are still protons and atoms and solids around us? The X particle is supposed to be billion times heavier than the proton. In an early hot universe ($T > 10^{18}$K) a part of radiation produced protons, passing above the X barrier. But the universe cooled down so fast, that proton-matter got trapped in the low S, high G state. Its delayed annihilation into radiation is calculated to need more than 10^{30} years for tunneling through the X barrier. This is why our present universe, stuffed by photons, still contains atoms as well.



MOUSETRAP NO 2: ATOMS VERSUS LIGHT. Let us remember the strudel (rubber) model of the Universe: if the size R(t) of the sheet is stretched, the wave length λ grows proportionally to R(t), so the momentum of a free particle drops like $mv = h/\lambda \sim 1/R$, in accordance to de Broglie's formula. Now for light: The energy of a proton $E = h\nu$ is proportional to kT and it is inversely proportional to λ, so the radiation temperature drops like $T \sim R^{-1}$. For a gas, on the other hand: The energy of a free atom $E = mv^2/2$ is proportional to kT. The speed is inversely proportional to wave length: $mv = h/\lambda \sim 1/R$; so the gas temperature drops like $T \sim R^{-2}$. If radiation is decoupled from the gas, a 10-fold increase of distances may mean a 1/10 fold fall of radiation temperature and a 1/100 fold fall of gas temperature. - The first million years the

electromagnetic radiation and the ionized gas were in interaction, they had equal temperatures. At the end of this era the gas became neutral and transparent for radiation, so the coupling was broken. The gas cooled faster, than radiation. In the cold gas gravity formed galaxies and stars.

MOUSETRAP NO 3: HYDROGEN VERSUS IRON. The atomic Universe contains today 75% hydrogen, the simplest nuclei. Cosmic matter got trapped in this state in the early hot era. At lower temperatures the Coulomb barrier separating the positive nuclei prevented their fusion. The core of stars

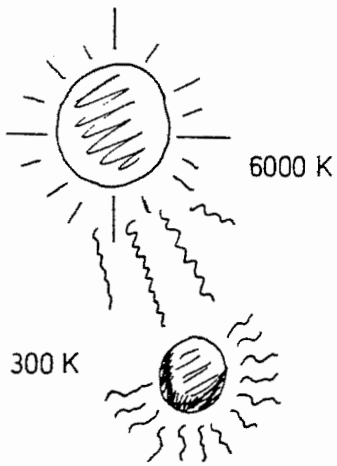


COULOMB BARRIER

offered a new chance for fusion at several million degrees. Thermonuclear fusion by tunnelling is very slow at this temperature, offering 10-100 billion years of starlight and sunshine. The biological machines exploit the temperature difference between the 6000 K hot sunshine and the 300 K cool atmosphere. The transformation of high energy hydrogen to low energy iron takes 10-100 billion years, this time scale is exploited by biological evolution.

Life

Our solar environment is now far from thermodynamical equilibrium. Sunshine (T_S = 6000 K) reaches the Earth.



The energy of Earth does not keep increasing, because the same amount of energy is radiated back to space from the soil in form of infrared radiation (T_E = 300 K). The entropy balance is given by the entropy loss of the Sun ($-Q/T_S$) plus the entropy change of the Earth (ΔS) plus the entropy gain of the outer space by terrestrial radiation ($+Q/T_E$):

$$-\frac{Q}{T_S} + \Delta s + \frac{Q}{T_E} \approx 0.$$

From this equation one concludes

$$\Delta s \approx -\left(\frac{Q}{300\ K} - \frac{Q}{6000\ K}\right) < 0.$$

Entropy may decrease on the surface of our planet. (This

is easy to be understood in statistical thermodynamics. The energy, arrived from the Sun in form of visible photons is given off in form of infrared photons. 20 times more protons leave than arrived, this enables the Earth to export its disorder.) The structure formation in open system is not in contradiction with the Second Law!

John von Neumann has proved (1953) that structures complex enough may be able to reproduce themselves. This opens a qualitatively new possibility in cosmic history. Let us consider a realistic structure (blue-green alga) which is able to reproduce itself in about 60 minutes by making use of sunshine. In 5 hours = 300 minutes this means five generations, i.e. 2^5 exemplars. In two days = = 50 hours this means 50 generations = 2^{50} exemplars. (Ideal food is assumed.) But in the "noisy" environment not all the copies will be perfect. The molecular collisions (Second Law) may produce misprints (less perfect structures), which need longer time, let us say, 75 minutes for reproduction. In 5 hours one gets only 4 generations = 2^4 copies, in 2 days only 40 generations = 2^{40} copies, 2^{10} = thousand times less than the offsprings of the perfect version! Missprints are eliminated by natural selection. Individuals decay and die, but the race does not age.

Let us assume that the environment changes (more sunshine or new minerals in the pond ...). By chance a misprint looses a certain segment of DNA, which is not necessary in the new environment any longer. It manages to make a copy of herself in shorter time: in 50 minutes. In 5 hours this means 6 generations, i.e. 2^6 copies. In two days = 50 hours it means 60 generations = 2^{60} exemplars. In two days the new creature has got 2^{10} = thousand times more offsprings than the original one! The race fits itself spontaneously to the new environment. Biological evolution does not contradicts the Second Law (necessity of missprints) but follows from it. On this way cosmic

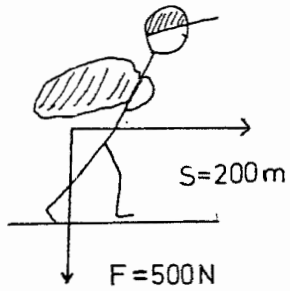
history might reached man.

"What is the work performed by the coalman while he carries 50 kg coal horizontally for a distance of s = 200 m ?" A hurried answer would be: "Force is perpendicular to displacement, consequently no work has been performed."

$$W = \vec{F} \cdot \vec{s} = 0.$$

I am not sure the coalman would accept this argumentation. He would say that he got tired and hungry, he would ask for his money. Who is right: physics or nature? Certainly they cannot contradict each other!

The coalman carrying 50 kg on his shoulders is far from the equilibrium state. Biochemical reactions run faster



in his body (producing entropy at a rate σ/t=1.5 watt/K) than at rest(σ/t = 0.3 watt/K). He has to get rid of the excess disorder in his body. The only way to get rid of entropy is to give off heat Q. Our coalman sweats, on this way his entropy balance is restored:

$$\Delta S = \sigma - \frac{Q}{T} = 0.$$

but his energy has been decreased! He has to take in energy (in ordered form W)to restore the energy balance, so our coalman must buy food, to get chemical energy and he must eat more:

$$\Delta E = -Q + W = 0.$$

We can get the answer to the above question: the work W (ordered energy input) can now be calculated:

$$W = Q = T\sigma = 300\ K * 1.5\ W\ K^{-1} * 300\ s = 50\ kJ.$$

Physics has explained Nature well.

On this way we can distinguish three levels of phenomena:

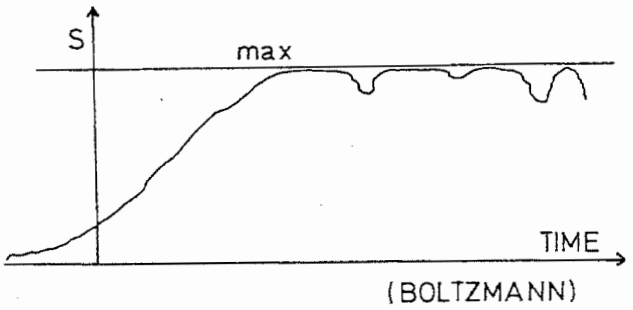
LEVEL ONE: Object with few degrees of freedom (rigid body, mathematical pendulum, single electron) can be described exactly by the equations of motion. These questions are symmetric with respect to time reversal $t \to -t$ (up to the accuracy of superweak interactions). These are reversible.

LEVEL TWO: Bodies, consisting of many atoms, need a statistical description, where the Second Law is valid: the total entropy increases during any real change. Each individual body wears off, decays, dies, its fate is irreversible.

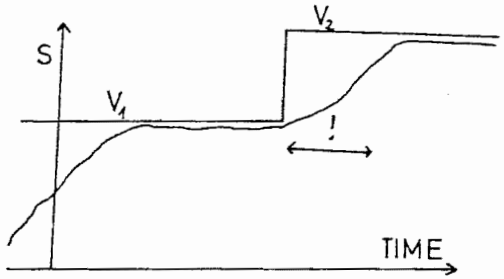
LEVEL THREE: Populations of selfreproducing structures (living beings, people, cultures, ideas) do not wear off. They eliminate misprints and keep fitting to the changing environment. The Darwinian evolution is also irreversible, but in an other sense!

Arrow of Time

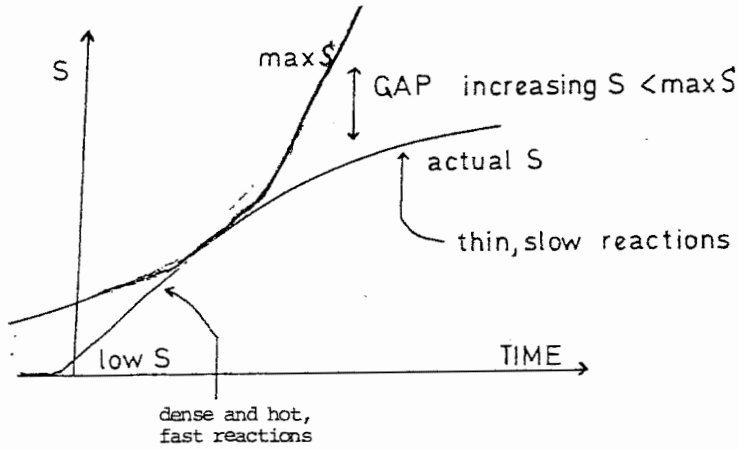
The conclusion of the 19th century was a geometric universe, existing since the eternity. In this world the entropy reached its maximum value (the heat death). A local resurrection might be caused only by statistical fluctuation (Boltzmann). This conclusion is, however, sharply contradicted by the astronomical evidence, obtained in the 20th century. We observe now a huge part of the universe, faraway regions which never were in causal contact and we never see a heat death, only the same deviation from maximum entropy everywhere.



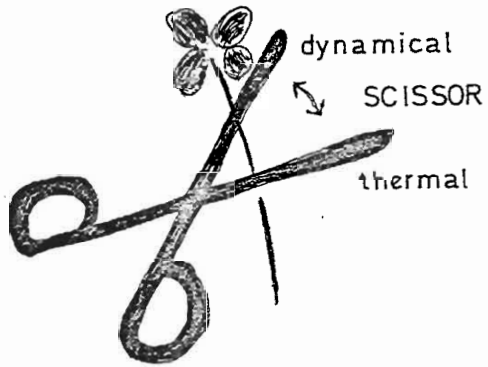
The conclusion of the 20th century is a dynamical universe, which gives a rational answer to the problem of the heat death. Let us consider a cloud chamber, filled with air and vapour. If we expand it suddenly from volume V_1 to V_2, the new (larger) maximum entropy state would be a cooler air with liquid water droplets floating in it.



But this new equilibrium state will not be reached immediately, due to the slowness of condensation. For a transition period we shall have overcooled vapor. This limited period is exploited when physicists use the cloud chamber as track detector.



The real Universe is in the state of steady expansion. The possible maximum value of entropy increases with increasing geometrical distances. In the early high density era the collisions are frequent, so the actual entropy reaches this maximum very soon: heat death in the early era. But later the density gets small, collisions become rare. The entropy keeps increasing, but is not able to reach the maximum. It is chasing a man who runs faster than you: resurrection in hte late era. It is a subject of intensive research today, to find out, if the Universe (after all the fluels got exhausted and all the protons decayed) will be able to reach again the state of maximum entropy (only cool radiation present) or the huge and increasing distances among particles will prevent their complete annihilation. We can say now that the two arms of the scissor (the maximum entropy curve and the actual entropy curve) have got opened, creating free energy G and offering the stage for the drama of life.



It is an everyday experience that the flow of time has a direction. The explanation of the arrow of time is a century old problem of science. In the present literature two explanations can be read:

THERMODYNAMICAL EXPLANATION: the direction of time is given by the increase of entropy. - This explanation is not complete, however, because in infinitely old universe entropy has had to reach its maximum, consequently time has lost its sense. We can hope only in fluctiations, but an entropy fluctuation has both: a descending and an ascending branch, so no clean time direction has been obtained.

DYNAMICAL EXPLANATION: Time is offered by the monotonous expansion of space. But such a dynamical change is certainly reversible! - None of the two answers is sufficient alone.

FULL EXPLANATION can be obtained by the interplay of the dynamical instability and the thermodynamical tendency for energy equipartition. If the universe is not in a steady state (steady solutions of the dynamical equations do not exist) the finite collision times produce transient deviations from equilibrium. If the Universe is not too hot and dense (if the earliest era is already over) then this transient period may last for billions of years (or forever). The Universe is changing dynamically, the entropy is increasing with a finite speed, and the interplay of these two phenomena produces transient phenomena like the biological evolution.

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CREATION AND DECAY

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and Lincoln College, Oxford, England

The deep structure of change is decay. One of science's most important contributions to our understanding of our own nature is not the concept of entropy (which, after all, is trivially easy) but the attitude that it may be applied to every activity in the physical world (there is, of course, no other world). We now know that the spring of the world is collapse into chaos: the spring is the chaotic, natural, dispersion of energy. Science has shown us that all the events in the discernable world (the only world) spring from chaos, and it has shown that the only problem that science now needs to attack is the manner of the gearing by which dispersal and collapse are transformed into the unfolding of a leaf, the formation of an opinion, and the foundation and elaboration of civilizations.

The view that I wish to impress upon you is that scientists and teachers have an intellectual duty to explain the role of entropy to others. We have to show not only that it accounts for little things, such as the cooling of a lump of hot metal, but that it also accounts for the big things of life, such as consciousness and the illusion of purpose. I think it is not much of an exaggeration to say that the Second Law (and especially its statistical interpretation) is science's greatest contribution to the liberation of the spirit. Now we can see that the formation of an opinion or the adoption of a belief are nothing more than elaborate forms of the purposeless, natural dispersal of energy.

The great advantages of entropy and the basis of the Second Law (insofar as we have to teach them) are that one is trivial and the other is obvious. Few subjects are so kind to the teacher! Their simplicity means that we need not hesitate to teach them in our schools. The concept of entropy as being related to the extent of dispersal of energy can be picked up by a child (happily others are considering the

the extremely subtle concept of energy itself).

There is, however, one difficulty with teaching entropy, and it is what I shall talk about here. Let me explain that my interest in entropy and the Second Law concerns their involvement in chemistry. I shall therefore concentrate on teaching the chemical implications of entropy, and talk about ways of presenting the basic ideas of chemical thermodynamics. In a sense chemistry lies almost exactly in the middle of the subject. On the one hand, explanations of chemical processes in terms of physical events draw on concepts that interest physicists and which are being discussed by others in this seminar. On the other hand, chemical processes are the basis of biological events, such as reproducing and thinking, which ought to interest everyone. In other words, my plan to talk about chemical aspects of entropy takes us some of the way along the path I have indicated earlier: the path from the trivially obvious processes and physics to their deeply extraordinary manifestations, such as civilizations. This is the thought behind the title of this lecture: on the one hand we have Creation, the emergence of order from slime, and on the other we have Decay, the natural, spontaneous, dispersal of energy. I want to explore the link, and show how chemistry can be used to illustrate that decay can be creative. That, in my view, is the one difficulty with teaching entropy: to show people that collapse there can generate order here.

I am conscious that I am speaking to an audience largely of physicists. What I should like to do is to expose some of the difficulties that we chemists have to consider when we are presenting entropy. The difficulties are associated with the fact that in physics events take place without changing the composition of the system, whereas in chemistry events involve changes of composition. I shall introduce the difficulties that arise, and make some suggestions about how to overcome them, but my suggestions will be very tentative and incomplete. I shall start with the physical aspects of entropy (which you all know about, but I want to present a complete story), and show how they can be extended to deal with chemical change. The particular chemical change I shall aim for is one which is deeply involved in living systems. In this way we shall travel almost completely along the path from decay to creation. At each stage I shall illustrate the point with a very primitive chemical reaction. I think it a good matter of

Fig.1

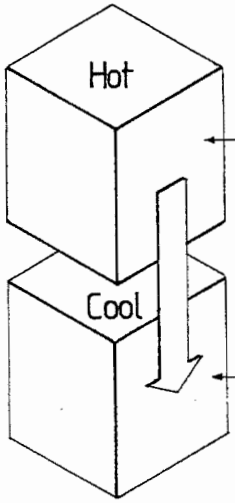
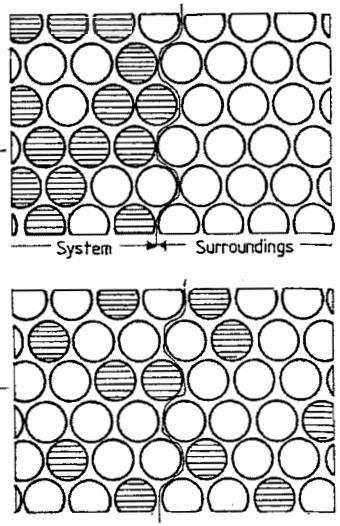


Fig.2



principle to use extremely simple processes to illustrate deep ideas, but I accept that this leaves open the danger that people will not see their connection with ordinary events in the real world.

1. Why things cool. Everyone knows that a hot object (such as a lump of metal) cools spontaneously to the temperature of its surroundings, Fig. 1. The explanation is extremely simple: a hot block consists of vigorously vibrating atoms, and as these jostle their neighbours in the surroundings the energy spreads away, Fig. 2. The energy initially in the block is jostled from atom to atom; it is shared with several atoms, and in due course is dispersed randomly over all the atoms it has access to. The observer reports that the energy has leaked away from the block: the atoms are now vibrating less vigorously; the block has cooled.

There is nothing easier to understand in science. We see that the jostling of neighbours, and the dispersal of energy it has brought about, Fig. 3, is a trivially obvious, natural, spontaneous process. We have decided to name the dispersal of energy entropy.

My point, let me emphasize it again, is that all change is nothing more than an elaborate form of the cooling of a lump of metal. All

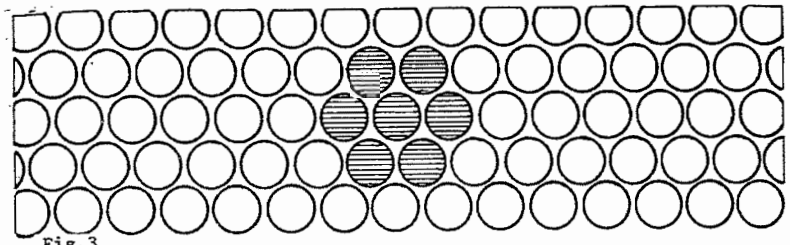
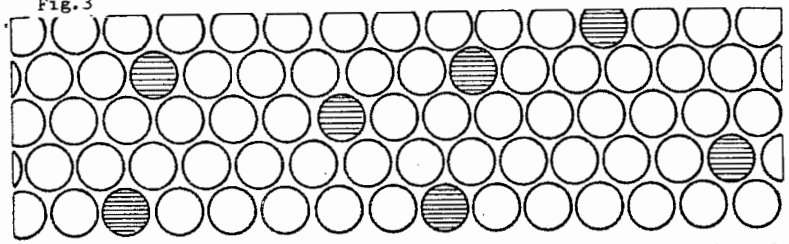


Fig.3



change in the world - the formation of an opinion, the presentation of a lecture, the unfolding of a leaf, and the reaction of two chemicals - is the manifestation of the collapse of energy into chaos. Of course, that collapse is geared together with astonishing richness, and the gearing is such that in local regions of space and time brains take decisions, societies build cathedrals, and orchestras perform symphonies; but these are all local abatements of chaos, and each one feeds off a greater production of chaos elsewhere. Of course, we do not yet fully understand the gearing that harnesses collapse and mani-

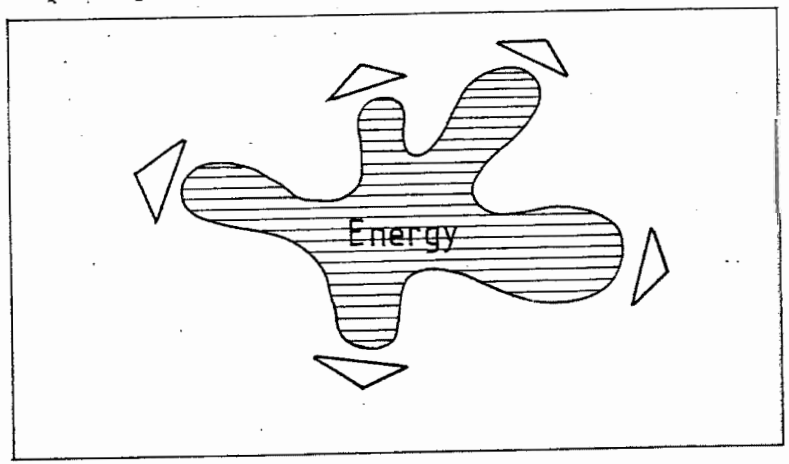


Fig.4

fests it as a brilliant opinion or a crime. But that is a detail. We can be sure that dispersing energy, increasing entropy, is a universal explanation of action, Fig. 4. That we cannot everywhere trace it from a molecule to a personality does not mean that we have not formulated the correct explanation of everything. I think it most important that in our teaching we convey this flavour of universal, simple explanation.

Another point is that if we think in terms of dispersal of energy we can go beyond equilibrium thermodynamics. This is important, because it lets us account for the process of change itself, not merely the ultimate position of equilibrium. In particular, the idea of dispersal takes us into the realm of systems far from equilibrium, such as living organisms. In this sense the statistical interpretation of entropy is much deeper, richer, and broader in its applications than the thermodynamic interpretation where the equations have been developed for reversible changes, and irreversible changes are largely expressed as inequalities, not equalities.

2. The deep structure of purpose. Now I shall go one step up in complication. Some events seem intentional. I intend to write this sentence. You may intend to sleep. I now intend to look at the deep structure of purpose, the illusion of intention in the world. We shall see it in its most primitive form, but that does not mean that we have oversimplified. The essence of all change must be simplicity, and explanations that look simple and obvious are not necessarily wrong (and, in my view, are more likely to be right than explanations founded in complexity and obscurity).

Illusions of purpose are modelled by different densities of states. I can illustrate this with the system shown in Fig. 5, which shows that apparently there is an intention of the energy in System 1 to migrate to System 2. What is the basis of this apparently purposeful action? We can see it as soon as we examine the systems more closely. System 1 has only a few platforms on which energy can stand, but System 2 has many. This means that when the energy is dispersed uniformly over all the available platforms, System 2 will have the lion's share. Initially all the energy is in System 1. It jostles and disperses in the usual way, and in due course becomes uniformly distributed throughout the available Universe. That uniformity, however, corresp-

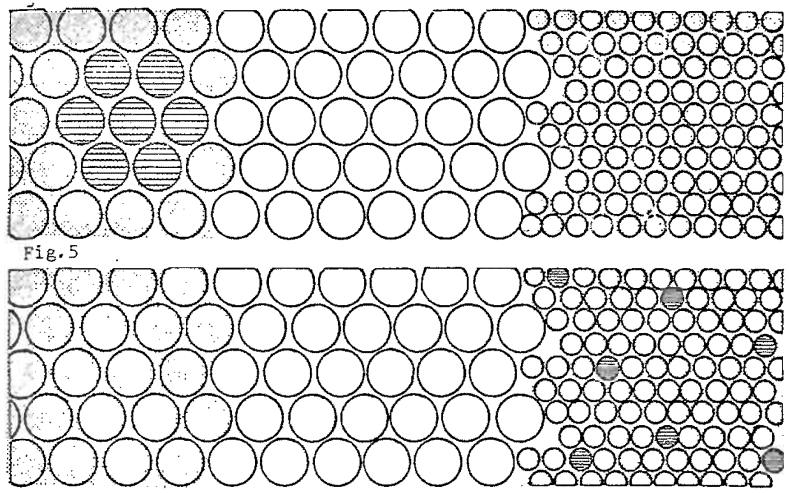


Fig. 5

onds to it being captured by System 2. The observer therefore sees that the energy has migrated from System 1 to System 2, and will conclude that it must have gone there for a purpose. We, however, who see beneath the superficiality, know that that purpose is an illusion: energy has done what is always does, given the opportunity: it has dispersed widely, randomly, and purposelessly.

All apparently purposeful processes are of this kind: they are ordinary dispersals, ordinary processes corresponding to the increase in entropy, but they give the illusion of purpose. Of course, some purposeful acts are extremely complicated. But they are all at root chemical reactions moving in the direction of increasing entropy. They are reactions taking place in that extraordinarily complicated test-tube, our brain, and their outcome is almost unpredictable, so complex is the manner in which the underlying simplicity emerges into the perceived world of actions and decisions. Nevertheless, at root, decisions are driven by dispersal.

2. Why things rust. Now I move to chemistry, and begin to apply the idea of dispersal to the processes of chemical reactions. All chemical reactions run in the direction of increasing entropy: all we have to do is to expose the simplicity under the complexity.

The chemical reaction that comes closest to the physical process that we have considered, the cooling of iron, is the rusting of iron (its oxidation), Fig. 6. Rusting, we shall see, is the chemical cool-

Fig.6

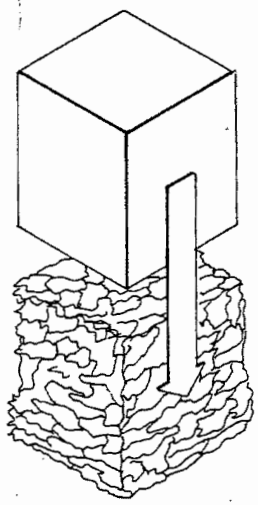
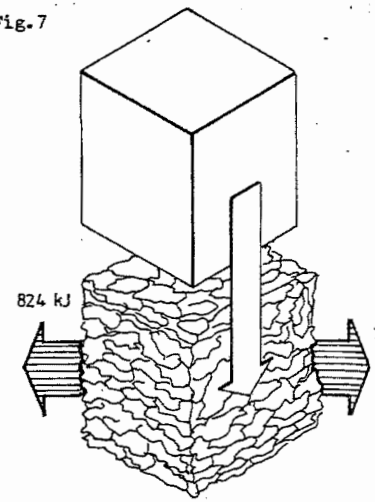


Fig.7

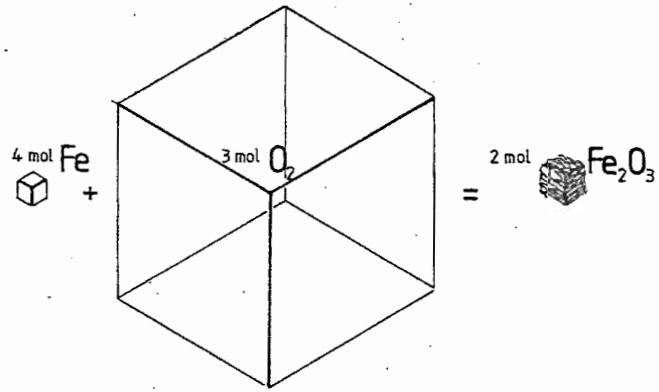


ing of iron. This attitude to the reaction makes it very easy to make the transition from physics to chemistry, and so at this stage the conceptual problems are minimal. Incidentally, rusting is like respiring: both involve the reaction of oxygen with iron, and so much the same argument as we shall now present applies to the basic life-giving reaction.

You can see that rusting (I shall call the oxidation 'rusting' although the actual reaction involved in destroying steel is slightly different) is chemical cooling by considering the energy changes involved. When an oxygen molecule collides with the surface of a block of iron the chemical bonds are reorganized and in place of Fe-Fe and O-O bonds we get Fe-O bonds and the formation of the oxide Fe_2O_3. This releases a large quantity of energy (the enthalpy of the reaction is -824 kJ per mole of Fe_2O_3). This released energy disperses into the surroundings, Fig. 7. The natural direction of change in the reaction is from the reactants, with the energy locked up in the bonds holding the metal together and in the molecules of oxygen, to the product, where some energy remains locked up in the highly localised solid (the heap of rust) but 824 kJ has jostled away and is spread throughout the surroundings.

But once we stop to think we see that there is more to the discussion than this suggests. This is where chemistry diverges from physics

Fig.8



(in practice, not of course in principle). For instance, the oxygen is initially present as a gas, and so its energy is spread over a large volume, Fig. 8. When the products have formed, all the oxygen is confined to a volume the size of the heap of rust. Furthermore, there is energy now locked up inside that volume in the iron-oxygen bonds. We can begin to see that there is a competition between, on the one hand, localisation of energy that occurs when the widely dispersed oxygen reacts to form a highly localized solid and, on the other hand, the dispersal of the energy that is released into the surroundings as a result of the reaction. This competition is in fact the basis of the subtlety of chemistry, and it will play an increasing role in what I have to say. In a sense, life itself is a competition, not in a Darwinian sense, but in terms of what process generates most entropy. Evolution is just a very elaborate form of dispersal.

In order to analyse the competition in the oxidation we have to know the entropies of the species involved. This is a major difference between physics and chemistry, and is the first difficulty a chemist has to overcome when presenting chemical thermodynamics at an elementary level.

Difficulty 1: How do we explain the different entropies of different substances.

What we have to recognize is that different species have different quantities of energy embedded in them, and that the energy within different substances is dispersed to different extents. This means that a lump of iron has a different entropy at high temperature than at low.

It also means that a lump of sugar has a different entropy from a lump of iron because of the greater complexity of the crystal and the molecule. Only at absolute zero (T=0) where there is no energy to disperse, do all perfect crystals have zero entropy. (Notice how the Third Law creeps in so naturally.)

Difficulty 1 is an interesting point and dealing with it could occupy a whole lecture: I simply draw it to your attention here, and say that straightforward laboratory measurements (or calculations) let us compile a list of standard entropies. The change of entropy when a substance like iron and oxygen turns completely into something else (rust) can then be calculated very simply by taking the appropriate combinations of values. (In passing I note that at this stage students are familiar with handling enthalpy data, and so can use entropy tables in the same way.) But it is very important to note, and I shall come back to the point, that the values normally reported refer to pure substances, not mixtures. In particular, it is easy to calculate that the change of entropy on going from pure iron and oxygen to pure rust (Fe_2O_3) is -225 J K^{-1} for 1 mol Fe_2O_3. As we anticipated, Fig. 7, there is a large decrease in entropy in the reaction because the highly dispersed oxygen gas has reacted to form a compact solid. (However, note the interesting point that we have been able to attach a numerical value to the reduction of the dispersal of energy brought about by the reaction: this is an extraordinary feature of thermodynamics, and should not go unremarked. Entropy quantifies chaos.)

Reduction of dispersal? Did I say reduction of dispersal? Why, then, is rusting spontaneous? Of course, the answer is that we have not taken into account the change in entropy of the surroundings. We know that this is large, because a great deal of energy is released as heat by the reaction. This is an extremely important point, and in our teaching we must always emphasize it: we always have to consider the total entropy not the entropy of one fragment of the universe, such as a reaction vessel or a person.

Just as we can put a numerical value on the dispersal of energy in compounds, so we can put a value on the energy dispersal in the surroundings. The magical formula is

$$\Delta S(\text{surroundings}) = -\Delta H/T.$$

Now we have another problem:

Difficulty 2: How do we justify this expression?

I think this difficulty (which of course occurs in physical processes too) is quite straightforward. In the first place, $-\Delta H$ is the energy liberated as heat by the reaction, and which increases the entropy of the surroundings because energy is pouring into them in a random, chaotic way. Secondly, the presence of temperature in the denominator is quite easy to explain: much more chaos is generated for a given injection of energy as heat when it is injected into a cold environment than a hot one: when you sneeze there is more disturbance in a quiet library than in a busy street.

The changes in entropy accompanying a chemical reaction can be obtained very easily from the information about reaction enthalpies that are widely available and familiar to the student. For example, since the standard reaction enthalpy for the iron oxidation reaction at 25°C is -824 kJ for the formation of 1 mol Fe_2O_3, the change of entropy of the surroundings is +2760 J K^{-1}. This is a massive increase in entropy. Therefore the total entropy change in the universe when 1 mol Fe_2O_3 is formed at 25 °C is

$$\Delta S(\text{total}) = \Delta S(\text{surroundings}) + \Delta S(\text{system})$$
$$= -\Delta H/T + \Delta S(\text{system}) = +2535 \text{ J } K^{-1}.$$

I shall make two points about this result. The first is that the overall increase is large and positive, and so the rusting reaction is spontaneous, as we all know. The second is a much more important pedagogical point. I shall present it as a difficulty:

Difficulty 3: How do we introduce the Gibbs function?

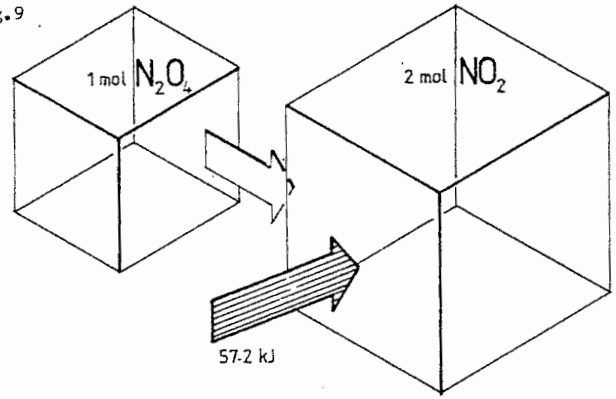
I think that, at this introductory level, the answer is quite straightforward. I favour the following argument. In order to arrive at the value of $\Delta S(\text{total})$ we have had to refer to two tables of data, one for entropies of substances and the other for their enthalpies of formation. That is a nuisance. It would be far simpler to combine the two sets of data into a single table. This we do by reorganizing the last equation into

$$-T\Delta S(\text{total}) = \Delta H + T\Delta S.$$

(I drop the label 'system' from now on.) The new quantity $-T\Delta S(\text{total})$ is now given a new symbol (ΔG) and a new name (the Gibbs function). Hence we arrive at

$$\Delta G = \Delta H - T\Delta S,$$

Fig.9



one of the most important yet most often misinterpreted equations in thermodynamics.

This way of introducing the Gibbs function eliminates a lot of its mystery (and its potential for misinterpretation) because it shows that it is simply a book-keeping device. I think it most important that when the Gibbs function is introduced it is presented merely as a helpful way of doing entropy calculations, and that it takes into account simultaneously and simply the changes going on in both the system and its surroundings. I think it equally important not to attempt to interpret the Gibbs function in terms of systems having a tendancy to decrease their enthalpy and increase their entropy: that is quite wrong, and annihilates the attitude I have been trying to establish.

3. Why things reach equilibrium. I now want to consider another type of reaction which exposes another important difficulty. Once again we have the problem that in chemical thermodynamics we have to deal with changing substances. This has very important consequences for determining whether or not a reaction will convert reactants entirely into products. In other words, what I now want to explore is the following:

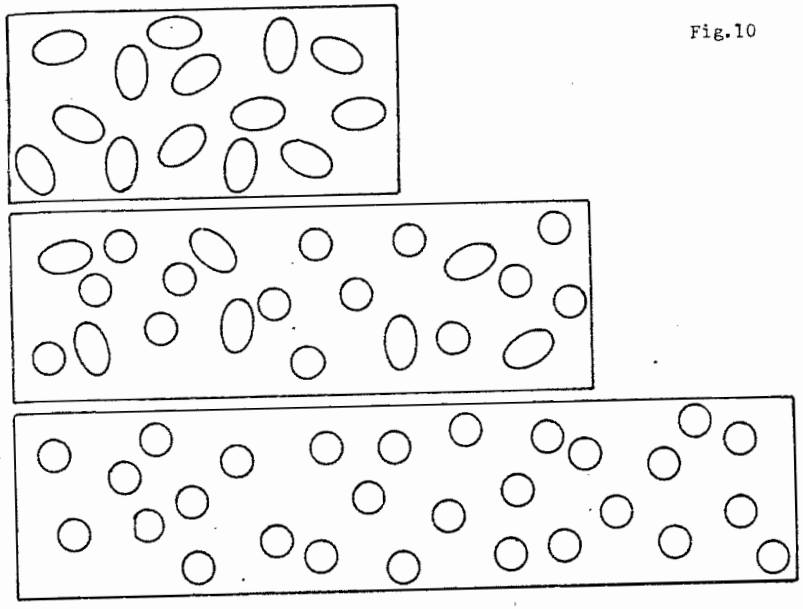
Difficulty 4: Why does a reaction appear to go only so far and then stop?

The reaction I shall consider in order to illustrate my point is another very simple one, Fig. 9:

$N_2O_4(g) = 2NO_2(g)$; $\Delta H^{\ominus} = +57.2$ kJ, $\Delta S^{\ominus} = +175.8$ J K^{-1}.

These figures imply that the change in the total entropy of the Universe when 1 mol N_2O_4 changes into 2 mol NO_2 at constant pressure is

Fig.10



-16.0 J K^{-1}. This is negative, and so we seem to need to conclude that the reaction does not go spontaneously. Nevertheless, in fact the molecule N_2O_4 does dissociate (to some extent), and so there must be some effect that causes the entropy to go through a maximum at an intermediate stage of the reaction.

The discussion so far has ignored the effect on the entropy of the system of having a mixture of gases present at intermediate stages, Fig. 10. When only pure N_2O_4 is present, the system's entropy is that of N_2O_4 itself; when both species are present there is an additional chaos in the distribution of energy because of the mixing of the two species. This extra contribution is zero when only N_2O_4 is present, rises to a maximum when equal amounts of N_2O_4 and NO_2 are present (because the contribution to the entropy is the same as the entropy of mixing of two ideal components, and so it goes as the normal $x_A(\ln x_A) + x_B(\ln x_B)$ law: the chaos is greatest when the species are present in equal abundance), and then falls to zero again when only pure NO_2 is present Fig. 11.

The overall change of entropy of the Universe in a chemical change therefore consists of three parts: the entropy change of the surrou-

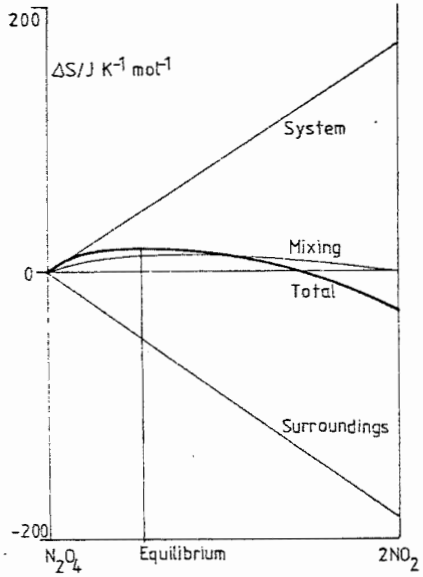


Fig.11

ndings, the entropy change within the system as molecules change their identity, and the entropy of mixing of the components. These three contributions are shown in Fig. 11 together with their sum. We see that the total entropy does indeed go through a maximum at a specific composition, and so this is the equilibrium state of the reaction. (The Gibbs function behaviour for the reaction is essentially the same curve upside down, because of the negative sign in $\Delta G = -T\Delta S(\text{total})$, and with a change of scale, because of the factor T: it conveys exactly the same information but, for our present purpose, in a more obscure way.)

4. How decay can create. The final problem I want to consider is the following difficulty:

Difficulty 5: How can chaos be constructive?

I think there are various ways of presenting this material. One way is to develop the concept of Gibbs function and to show that it is the free energy. This is something I have not touched on in my lecture because it would take too long. Nevertheless I should like to take the opportunity to mention that I regard it as a very challenging aspect of teaching chemical thermodynamics to find elementary ways (and by elementary ways I mean ways that shows the teacher knows what he is

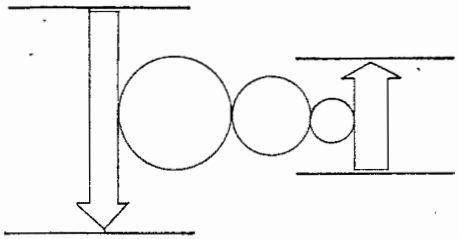


Fig.12

talking about!) of making the link between ΔG and available nonexpansion work. Once again, this can be done in terms of the increase of the dispersal of energy, and you will all be familiar with the underlying ideas. I do not have time to say any more than that the idea of ΔG as being free energy leads on to the concept of exergonicity, and then to the idea that if reactions are coupled together, the more exergonic may drive the less in an unnatural direction, Fig. 12. An argument can then be traced which justifies eating in order to think.

The alternative route round the difficulty is to explore the constructive potency of chaos by looking at a simple process which entropy appears to drive in the wrong direction. This is in line with the theme of the rest of my lecture, where I have been trying to locate primitive, fundamental, examples, each of which conveys the essence of the concept I am trying to establish. The simple process I shall start with is a physical one; then I shall show its chemical (and in this case biological) analogue.

The question I invite you to consider is why oil does not mix with water. The standard explanation is that hydrocarbon-water bonds are less favourable than water-water and hydrocarbon-hydrocarbon bonds, and so energetic considerations favour nonmixing. There are two things wrong with this argument. One is the philosophy of the answer: we should never discuss spontaneous processes as though they were driven by a tendency to lower energy. That is, in order to think about the reason why oil and water do not mix, we should find an entropy argument. The second error in the argument is the information it is based on: in fact mixing is an exothermic process for many hydrocarbons, and so contrary to the normal supposition, bonds between water and hydrocarbons are stronger than those between hydrocarbons! In other words, if we were to admit the validity of the 'tendency to lower energy' argument,

Fig.13

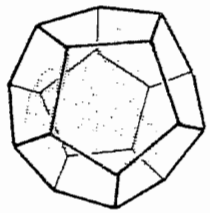
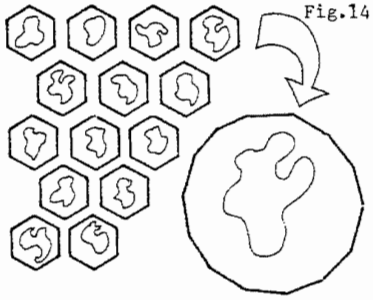


Fig.14



we would have to conclude that oil and water do mix!

In order to identify the true reason why oil and water do not mix we have, as always, to consider entropy. The major contribution to the change of entropy when oil droplets are present in water is their effect on the local structure of the water that surrounds them. When a hydrocarbon molecule goes into solution it builds a cage of water molecules around itself, Fig. 13. This decreases the entropy of the surrounding water because the water molecules have had to become more ordered in order to form a cage. The effect of a single large droplet of oil on the entropy of water is less than the effect of the same amount of oil dispersed as a myriad of droplets or as individual molecules (simply on surface to volume ratios), Fig. 14, and so the process of oil mixing with water corresponds to a very substantial decrease of the system's entropy. This increase is enough to overcome the increase of entropy of the surroundings resulting from the release of energy into them by the exothermic process. In other words, oil and water do not mix on entropy grounds. We can think of the entropy of the water as causing the molecules and droplets of oil to be squeezed together in an apparent opposition to the tendency for dispersal but

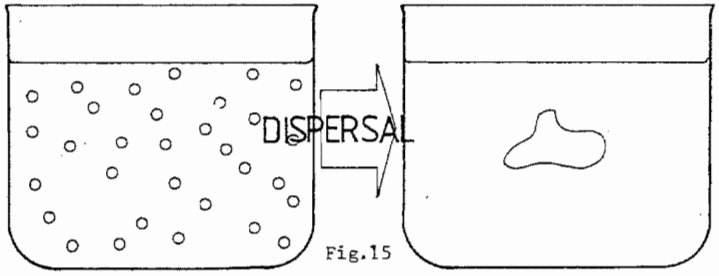


Fig.15

Fig.16

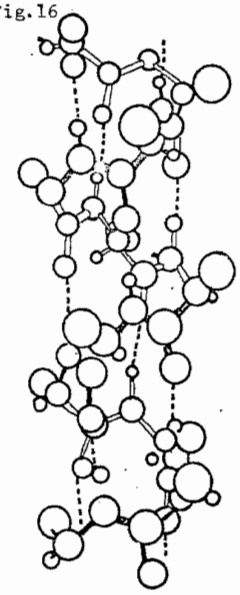
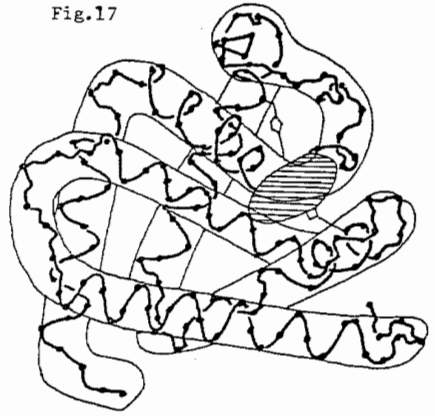


Fig.17



actually in accord with it. In this instance, entropy appears to have caused the opposite of dispersal, because a dispersed oil has a natural tendency to form a single blob, Fig. 15.

Water's entropy affects the structure of proteins. This is the link I want to mention in this final part of my talk. Proteins consist of long chains of amino acids strung together, and then twisted into a spiral (the α-helix) by hydrogen bonds, Fig. 16. This α-helix is itself twisted and buckled into a precise, characteristic shape. This is biochemically essential, because proteins carry out many biochemical processes, and after a molecule has been captured, it has to be doctored in a precise order of events. An enzyme molecule is a bit like a production line on a factory floor: the jobs have to be done in a precise order, and atoms and groups of atoms have to be snipped off or attached in a precise moment. Structure and function are inextricably linked in biology. An example of a protein molecule is hemoglobin, which consists of a group of four protein strands like the one shown in Fig. 17, and the shape of the bent, twisted α-helix is a crucial aspect of its function in transporting oxygen in the blood.

The shape of that precisely folded α-helix has been bought at the

expense of water's chaos. Many of the amino acids along the α-helix have hydrocarbon tails, and so locally they are like droplets of oil. The molecule in the cell is in an aqueous environment, and so exactly the same process that causes oil droplets to cluster together causes the amino acid tails to cluster together too. As a result, the α-helix folds and buckles, it adopts its precise and important shape, and lets us breathe. This is just a tiny example of the way that decay, the dispersion of energy, can lead to creation, the attainment of structure.

5. Conclusion. I hope I have covered the ground I promised. I promised to explore some of the difficulties that arise when we encounter entropy when trying to teach the fundamentals of chemistry. On the one hand I have tried to relate everything back to the physical process underlying all change, and on the voyage we have never been far out of sight of the land of physics. On the other hand, I have tried to show, in terms of examples that are extremely primitive but nevertheless important and revealing, how entropy plays out its role in the chemical and biological world. In this world chaos masquerades at least briefly as structure, and the tendency of energy to disperse emerges as an extraordinary richness. We have a duty, I believe, to share the insight that exposes the source of this richness. Far from diminishing our perception of the world, people should be awestruck at the realization that it is all so simple.

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I have based this lecture on material from three of my books:

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THE SECOND LAW (AND ESPECIALLY ITS STATISTICAL INTERPRETATION) IS SCIENCE'S CREATEST CONTRIBUTION TO THE LIBERATION OF THE SPIRIT.

Peter W.Atkins

ENTROPY, ECOLOGY AND THE CONCEPT OF SELF-ORGANIZATION

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Daughter: You said that we only make the parts of any whole.
Father: No, I said that parts are useful when we want to describe wholes.
(Gregory Bateson, Mind and Nature)

In recent years several concepts within science have emerged which indicate a movement beyond the positivistic tradition predominant in scientific institutions. New developments view nature as a process, not as a catalogue of fixed structures as commonly learned from the conventional methods of observing, classifying and generalizing - the rigid algorithm of empirical research. The paradigmatic shift to process dynamics can best be characterized by the term 'self-organization', as used by the researchers in this area.

Three scientists have, among others, contributed to the transition from closed systems in equilibrium to systems of open evolution: Ilya Prigogine, Hermann Haken and Erich Jantsch. Prigogine's book "From Being to Becoming - Time and Complexity in Physical Sciences" (1980) discusses the concept of time, especially with regard to irreversible processes, and introduces his own scientific work in the field of non-linear thermodynamics far from equilibrium for which he received the Nobel prize in chemistry in 1977. Additionally, his other book "Dialogue with Nature" (1981), embodies the scientific theories in a frame of the corresponding philosophical and cultural ideas. The physicist Haken has introduced the term "synergetics' for his theory of cooperative effects and phenomena in multi-component systems, as presented in "Synergetics. An Introduction. Nonequilibrium Phase Transitions and Self-Organization in Physics, Chemistry and Biology" (1977). The work of the astrophysicist Jantsch is dedicated to concepts of evolution as a universal key principle and is outlined in "Design for Evolution: Self-Organization and Planning in the Life of Human Systems" (1975) and in "Die Selbstorganisation des Universums" (1979).

The concepts of self-organization emerged from the natural sciences, thus being based on experimental research, along with a more integral view of the history of nature. Prigogine points out that the classical concept of a simple and passive world (in which nature is the mere object of human operations) is no longer valid not for reasons of philosophical critique or empirical resignation, but because of developments in science itself. Thus, a variety of natural processes do not follow the classical equilibrium-thermodynamics model of the 19th century. This allowed for the introduction of thermodynamical concepts dealing with processes near equilibrium and, ultimately, far from the equilibrium state.

In Newton's world of dynamics all systems, irrespective of their size or internal structure, obeyed the same mathematical principles of motion. This realm is governed by reversibility: objects can move from position A to position B and back. His clockwork-world was universal, closed and complete. Nature was no longer chaotic, lawless and stochastic, but lawful, obedient and predictable. The world outside was a world hard, cold, colorless, silent, and dead; a world of quantity, a world of mathematically computable motions in mechanical regularity. The world of qualities as immediately perceived by man became just a curious and quite minor effect of that infinite machine beyond.

With the development of heat engines, i.e. 19th century thermodynamics, heat became the rival to gravitation. The objects in the universe and the gravitational laws which they obeyed, that is the individual bodies with their modes of movement, were no longer central. Instead, the thermodynamical view focussed on particle populations with all their complexity. Based on the work of the French engineer Sadi Carnot, who advanced his concept of heat engines in 1824, the German physicist Rudolf Clausius established the Second Law of Thermodynamics with 'entropy' as a measure of degraded, inaccessible energy produced by every transformation of free energy. The second law states the tendency in all

processes of nature towards maximal entropy. The final outcome is a state where all energy is latent, that means unavailable for mechanical work - the state of heat death. Or, according to the statistical approach of Ludwig Boltzmann in Austria (who recognized heat as a random motion of the atoms), towards systems in which maximum randomness has the highest statistical probability. Boltzmann's redefinition of entropy covers not only energy but also material structures: nothing is destroyed (The First Law of Thermodynamics), but everything is scattered to the four winds - the universe tends towards Chaos. Since the laws of mechanics cannot account for a unidirectional movement, Newton's reversible world had been succeeded by processes which follow a one-way street - in the words of the British astrophysicist Arthur S. Eddington: "Entropy is time's arrow". Ernst Mach, Wilhelm Ostwald and others suggested giving up the laws of dynamics in view of the second law. Boltzmann's revival of entropy in the frame of a kinetic theory combined both dynamical and probabilistic aspects. Nevertheless, as most applications of thermodynamics were limited to equilibrium, the concept of irreversibility and minimum of free energy dominated the understanding of nature.

But, just as Newton's physics lead to two 'books of nature' (on the one hand the quantities resulting from experimental measurement and on the other the qualities of sensual perception as indicated in the Goethe-Newton debate on the nature of light), equilibrium thermodynamics also presented a divided world. Its concept of development appeared to be in contrast to the phenomena of life. According to the law of entropy, developments towards increasing order were highly improbable. Evolution, however, implies growing complexity. Thus, the statistical disappearance of particularity seemed incompatible with the statistical selection of rare configurations.

Ilya Prigogine's theory establishes a new level of viewing nature's processes, a level which links Newton's mechanics, Clausius' thermodynamics and Darwin's evolution. This level recognizes non-equilibrium as a source of order. Prigogine employs the term 'dissipative structures' for

the concept of self-organization of matter in open systems far from equilibrium. This concept no longer restricts matter to complete determination as in Newton's majestic clockwork nor to the running down of the universe as implied by the entropy law. It introduces the notion of qualitative movement to the seemingly inanimate sector of nature, the topic of the physical and chemical sciences. The problem of irreversibility and increase of entropy generated Prigogine's conceptual scheme for the production of distinct configurations: in situations far from equilibrium, fluctuations can take hold of the entire system and thus establish a new structure.

Hermann Haken studied cooperative phenomena in a variety of fields. His theory of synergetics stems from the observation and analysis of different systems when they pass through an instability threshold. The resulting instable collective motions establish different modes which serve as order parameters determining the macroscopic behaviour of the entire system. The degrees of freedom experience an enormous reduction by the fact that the mode competition leads to the government of one mode which, in turn, might yield to another one: this interplay drives the system from its previous state into new ones and determines the configuration of the intermediate (or final) establishment. Haken presents the theory of Laser, to which he has contributed a great deal, as an example for the dynamic competition and cooperation of the system's modes: in a gas-discharge tube (for example a neon lamp) the electrical energy of the power supply excites the neon atoms to a higher energy state. On returning to the ground state the atoms emit non-coherent light waves in all possible directions. This may be compared to the throwing of pebbles in a pond causing irregular motion of the water surface. Increasing the amperage of the tube leads to the excitement of more and more atoms thus one would expect the atoms to entangle in a spaghetti-like mess, comparable to the pond water being brought to "boil" by intensifying the pebble-throwing. Instead, however, after passing a certain threshold of intensity, the laser arrangement leads to a parallel and highly coherent beam restricted to a very narrow band of frequencies. The beam resembles a single giant wave track resulting from in-phase oscillation of the atomic antennas.

Haken's example employs the following analogy: little men equipped with sticks are standing by a water channel. Independent of each other they strike the water with their sticks. The, thus, irregularly agitated water resembles the diffuse light of a lamp. In order to achieve the similiar effect found in the laser equipment, they have to strike simultaneously, thus producing a regular, homogeneous wave. The little men could attain their synchronous action by employing a metronome or by choosing someone to give them the order, "now, now, now!". In the case of the laser atoms, however, there is no one giving orders. One could also imagine the little men striking whenever a certain wave reaches its highest peak, thus pushing the wave higher and higher. This self-regulated action, in alliance with the wave, suits the analogy best: the laser atoms organize their conduct themselves.

Finally, Erich Jantsch has explored and developed the dynamic principle of self-organization from the origins of living matter to the sphere of human reasoning. His "pattern which connects" (Gregory Bateson) demonstrates the formation of well organized structures in systems which pass from a state of disorder to order, a principle not only of the biological but also of the inanimate world. The process nature of this pattern is indicated by the key concepts of self-organization, co-evolution, self-transcendence and creativity. These concepts constitute continual evolution along with its characteristics on all levels: openess, non-equilibrium and autocatalysis. Openess refers to the principle role of open systems with respect to their evolutionary potential towards the formation of new structures; non-equilibrium marks the dynamics involved in situations of broken symmetry and autocatalysis, finally, depicts the self-reinforcement of fluctuations in the open system.

There are numerous examples for the dynamic existence of structures beyond the threshold of instability, for well organized spatial, temporal or spatial-temporal structures arising out of disordered

states. The Bénard instability, for instance, demonstrates an open system: a fluid layer is heated from below. When the temperature gradient reaches a critical value, the fluid starts a macroscopic motion - the heated parts are buoyed up, cool and fall back again to the bottom. This motion, from an originally homogeneous state, leads to well organized spatial patterns which in turn yield to new patterns due to increases to temperature. The mode of convection is governed by non-linear equations: beyond a critical value of the temperature gradient, each mode is far from the thermal equilibrium as the convection exceeds the conduction of thermal energy within the different fluid layers. The non-linearity of the total system supports the establishment of defined, dissipative structures. This new order by fluctuation is stabilized further by energy exchange with the surroundings. Similiar phenomena occur in fluid dynamics with respect to the switch from laminar to turbulent currents, where the portrait of a fluid flowing round a cylinder in wind channel fashion depends on the speed, thus exhibiting different patterns. In both cases we are dealing with open systems which are subjected to energy flux through the system in random fashion and show collective behavior of the components by forming well-defined macroscopic structures.

Both examples above depend on an external energy source, in these cases the systems behave in a distinctive manner to the energy flux passing through. However, most biological interactions and a number of physico-chemical reactions maintain their dissipative self-organization "by themselves" by means of autocatalytical processes. A famous example of this process is the Belousov-Zhabotinsky reaction, in which the oxidation of malonic acid by bromate in the presence of cerium ions leads to temporal oscillation: the solution changes periodically from red (indicating an excess of Ce^{3+}) to blue (indicating an excess of Ce^{4+}) and shows characteristic spatial patterns. The oscillation occurs as a long lasting, transitional state after the reagents have been put together. In a considerably simplified model for the reaction above a molecule of kind A reacts with a molecule of kind B to produce an additional molecule B. Since a molecule B is produced by the same molecule B as a catalyser, this process is called "autocatalytic reaction". A more elaborate and adequate model of the reaction would

show features which are also the background for the hypercycle theory of Manfred Eigen. This model provides an understanding of the origin of living matter by recognizing non-linear, autocatalytic systems as condition for development and gives an account of the evolutionary interplay in terms of molecular competition and cooperation. These systems meet the quality of autopoiesis (the Greek word for self-creation) and are characterized by a certain autonomy with regard to their environment, thus maintaining a self-reflective productivity in which the surrounding plays a minor role. In autopoietic words: the natural law of self-organization governed the origin and prebiotic evolution of life. By the evolution of man, nature has developed her own eye for self-reflection: autopoiesis has enabled nucleic acids and proteins to look at themselves.

It is apparent that the entropy concept is far too rough a tool to cope with the phenomena of autopoiesis. In the following an attempt will be made to outline several theses regarding the consequences of the concept "self-organization" for science instruction.

1) Understanding in terms of self-organizing systems weakens the drawn division between various science branches and provides an integrative tool for teaching science. The synergetic principle enables the exploration of analogies within the frame of an interdisciplinary field of research. Thus, the distinction between the "hard" and the "soft" sciences yield to a more integral view.

2) Traditionally, entropy and evolution are restricted to their respective fields. According to thermodynamics laws, structures in non-living nature tend to crumble with time, whereas evolution states that the complexity of living matter increases with time. As both entropy and evolution are considered basic concepts of nature, the contradiction is solved by reserving thermodynamics for isolated systems (in the "dead" sciences chemistry and physics) and evolution for the open, living, metabolic systems in biology. One important function of the theory of dissipative structures is to demonstrate that systems of inanimate nature can also be feedback-stabilized entities that maintain stability and productivity by building up an individual organization against the "ravages of time".

3) The Second Law is not restricted to the sciences as it has been an anthropomorphic concept from the beginning. More and more it is being used in the arenas of ecology and doomsday-futurology. As we have experienced, science instruction not only mediates the "facts of knowledge" but also provides a rationale along with the facts. The philosophy of entropic visions is well represented in the phrase of P.W. Atkins (Oxford): "The deep structure of change is decay" or in Jeremy Rifkin's "Entropy - A New World View". In contrast to the universal claim of the unescapable degradation of matter and energy, it is essential for science instruction to demonstrate the limitations of entropy with respect to present and future creativity of both living and inanimate matter. Understanding the concept of development is a prerequisite for the constructive notion that our world is not one of irreversible corrosion (whatever we may be doing) but still demands our knowledge and activity. Thus, the often referred to "limits of growth" attain embodiment in a larger framework that contemplates both the limits and the evolution of structures, finally leading to a "growth of limits" by means of dynamic processes in nature and history.

4) The introduction of autopoiesis in the physical sciences gains anthropological value in education when considering the extremes as outlined at the beginning: the complete determination of man in the world of dynamics (leading to the mechanical materialism of La Mettrie in "L'homme machine") and the randomness of man, subjected to chaos and insecurity with the only natural and certain condition facing him - his own death. In contrast to these two prospects autopoiesis links the freedom of dissipative structures with the "progress in consciousness of freedom" (Hegel) of mankind.

5) Science, boiled down to reduced structures and meagre internal logic, is limited when faced with the diversity and richness of life. The theory of self-organization and its explanatory function with respect to growing complexity in scientific fields provides a bridge for openess towards problems in the social sciences. This scope implies the productive funeral of C.P. Snow's thesis of the two cultures (which has contributed much confusion on discussing science and the humanities), thus giving a new perspective for both nature and history.

Final thesis: qualitative concepts of nature, an example of which can be seen in the theory of self-organization, are essential for a future non-alienated metabolism with nature. The qualitative "nature of nature" opposes any termination of nature's cycle, be it the mechanical clock-work or the tendency towards scattered dust, as the ascent of man depends on corresponding with nature as a world in becoming.

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AN UNDERSTANDING OF THE ORIGIN OF LIVING MATTER HAS BEEN PROVIDED BY RECOGNIZING NON-LINEAR, AUTOCATALYTIC SYSTEMS AS CONDITION FOR DEVELOPMENT AND BY ACCOUNTING THE EVOLUTIONARY INTERPLAY IN TERMS OF MOLECULAR COMPETITION AND COOPERATION.

THE THEORY OF DISSIPATIVE STRUCTURES DEMONSTRATE THAT SYSTEMS OF NATURE CAN ALSO MAINTAIN STABILITY AND PRODUCTIVITY AGAINST THE RAVEGES OF TIME.

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INFORMATION AND ENTROPY

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Introduction

Generally in teaching physics entropy is treated as a phenomenological quantity. However, only when entropy is introduced as a statistical quantity is there a possibility to understand its real nature. Among the different statistical approaches the one given by information theory seems to be the most distinct and consistent way which at the same time gives a general starting-point. This way of presenting entropy allows the student to understand more profoundly that entropy is a more fundamental quantity than temperature.

In the following we shall show how entropy can be employed in a simple way starting from information theory. We believe that this is also the simplest way to teach students the various applications of entropy even at school level. This is of importance because entropy and information theory have various applications and uses outside of thermal physics.

In information theory the main interest is focussed on the communication process and its optimal realization, whereas the source of information and its semantical features are not considered. In thermal physics the situation is exactly the opposite. The real interest is particularly in the source of information which source is the system under consideration. Communication process and its optimal realization are not considered at all.

1 Probability and Information

Here information means knowledge about a certain property of the system. With the aid of a simple thought experiment we will first show how information can be connected with true probability (f, $0 \leq f \leq 1$) so that a quantitative measure for information $I = I(f)$ can be obtained.

Let us consider a box containing a total of g identical cells. Let us assume that there is one particle in the box. The probability that the particle is in a certain cell is $f = 1/g$. The bigger the number of cells the smaller is the probability that the particle is found in a certain cell. If an observation is made and it shows that the particle is in a certain cell the information thus obtained is the bigger the smaller the probability. Therefore, the quantitative definition of information should fulfil the requirement that a decrease in probability corresponds to an increase in information: $dI/df < 0$.

An analytic expression for information has to fulfil another condition. Let us consider two separate cell systems, A and B. Each system contains one particle: particle a in system A and particle b in system B. Let the probability that the particle a (b) is in a certain cell be f_a (f_b). The corresponding values of information are $I(f_a)$ and $I(f_b)$. Now, a natural requirement is that the total information is the sum of the partial informations: $I = I(f) = I(f_a) + I(f_b)$, i.e., information is additive.

The joint probability of two independent probabilities occurring at the same time is the product of the individual probabilities: $f = f_a \cdot f_b$. The only possibility to transform a product to a sum is to take logarithms: $\ln f = \ln f_a + \ln f_b$.

In thermal physics we prefer the use of natural logarithms. (In information theory the logarithm with basis two is used because of the binary choices.)

Now, we can give the exact definition for information:

$$I = -\ln f \qquad (0 \leq f \leq 1)$$

Thus, information is always positive. Furthermore,

$$I = -\ln f = -\ln f_a - \ln f_b = I(f_a) + I(f_b)$$

We conclude that this definition obeys the requirement of additivity and, also, the first requirement: $dI/df = -1/f < 0$.

2 Entropy and Information

The thermophysical system is dynamical, its instantaneous exact state varies continuously. A certain true probability f_i ($0 \leq f_i \leq 1$) can be attached to each state. Here f_i gives the probability with which the system can be assumed to be in a state i at a certain moment.

In the equilibrium state the probabilities obtain exactly defined values which are determined by the energy levels of the quantum states. When the exact distribution of the probability values is known the state of the system is known to a large extent. Since the existence of the system can be taken as a certainty the distribution of the probabilities has to fulfil the normalization condition

$$\Sigma f_i = f_1 + f_2 + \ldots + f_n = 1$$

A certain state i of a thermophysical system is associated with the probability f_i and information $I_i = -\ln f_i$. Entropy (S) can now be taken as proportional to information. Entropy of the quantum state i is thus

$$S_i = kI_i = -k \ln f_i$$

The coefficient k is the Boltzmann constant. Thus, entropy quantitatively gives the extent by which one has had to abandon the effort of transferring information.

In thermal physics one does not consider the detailed behavior of individual particles or particle groups. Knowledge of the exact state of the system at every instant often requires a large amount of information. To obtain this information would be overwhelming and, therefore, it is appropriate to abandon this requirement.

3 Average Values

The average energy of a system is simply the weighted mean of the energies of the instantaneous states: $U = \Sigma f_i U_i$. Here U_i is not a function of the probability f_i. Similarly, the average entropy of the system is the weighted mean of the instantaneous entropies:

$$S = \Sigma f_i S_i = -k \Sigma f_i \ln f_i$$

In the equilibrium state the average entropy is constant. On the other hand, the instantaneous entropy ($S_i = -k \ln f_i$) generally fluctuates even in the equilibrium state.

It is important to note that probability f_i occurs in the expression for the average entropy in two places. On one hand, it is a weight factor with which the instantaneous entropy is multiplied. On the other hand, it determines the value of the instantaneous entropy. This dual role of probability brings about the special and even surprising properties of entropy.

4 Entropy of an Isolated System

There are two important theorems connected with the entropy of an isolated system.

Theorem 1: The instantaneous entropy of an isolated system does not fluctuate in the equilibrium state. It is constant and, thus, equal to the average entropy.

To prove this theorem we first note that the energy must be constant: $U_i = U$. From this it follows that the probability is constant, too: $f_i = 1/g$, where g means the number of possible quantum states. Now,

$$S_i = -k \ln f_i = k \ln g = \text{constant}$$

and

$$S = -k \Sigma f_i \ln f_i = -k \Sigma (1/g) \ln (1/g) = kg (1/g) \ln g$$

$$= k \ln g \qquad (g \geq 1)$$

Thus, the instantaneous entropy is equal to the average entropy ($S_i = S$) and does not fluctuate.

The expression $S = k \ln g$ is often taken as the statistical definition of entropy. It is to be noted, however, that it is strictly valid for isolated systems, only.

Theorem 2: The average entropy of an isolated system increases during an irreversible process and reaches its maximum value in the equilibrium state.

To prove this theorem, we employ a new variable $x_i = 1/g \cdot f_i$. Using the fact that $\ln x < x - 1$ $(x \neq 1)$ we first note that

$$\Sigma f_i \ln x_i < \Sigma f_i (x_i - 1) = \Sigma f_i x_i - 1 = \Sigma (1/g) - 1 = 1 - 1 = 0$$

Thus, $\Sigma f_i \ln x_i < 0$

The expression $S = -k\Sigma f_i \ln f_i$ for the average entropy is valid whether the system is in equilibrium or not. In equilibrium $f_i = 1/g$ and entropy $S_o = k \ln g$. Now,

$$S/k = -\Sigma f_i \ln f_i = \Sigma f_i \ln (g x_i) = \Sigma f_i \ln g + \Sigma f_i \ln x_i$$

$$= S_o/k + \Sigma f_i \ln x_i$$

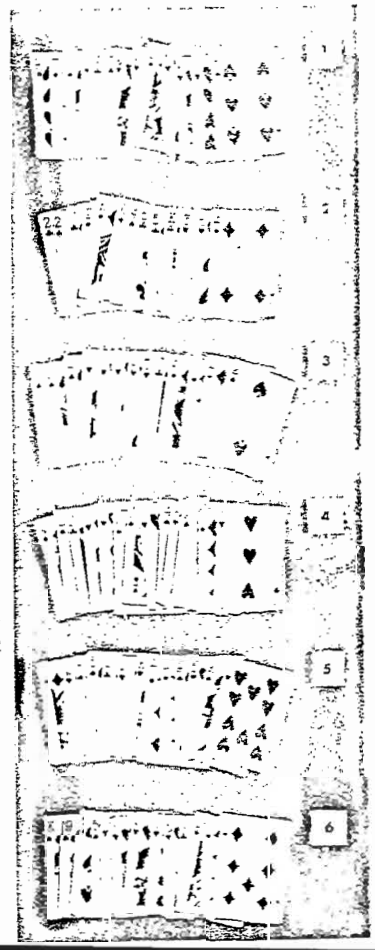
Thus,

$$(S - S_o)/k = \Sigma f_i \ln x_i < 0 \quad \text{and} \quad S_o > S$$

i.e., entropy reaches its maximum value in the equilibrium state.

With the aid of a more detailed approach it can be shown that during an irreversible process entropy will increase monotonically with time: $dS/dt > 0$.

from PSSC Advanced Topics ←



In Section 2-5, three different expressions are used in connection with the marble experiment: arrangement, state, and distribution. Figure 2-15 shows six hands of bridge. Identify cards with marbles and suits with slots.

(a) How many different arrangements are there?

(b) How many states?

(c) How many distributions?

ENTROPY AND THE IDEA OF SUBSTANCE

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INTRODUCTION

In this introduction to the problem of entropy I want to concentrate upon the part which is played by the idea of substance. Perhaps it is an unconventional approach to the problem which is occupying us. But it is an approach that "pays", for, in my opinion, it is our common sense understanding of what is meant by "substance" and by the "identity" of a "piece of substance", which is the cause of a problem encountered with regard to the concept of entropy. I assume for the moment that this problem - the world view implied - is more or less known. Some people call it a pessimistic world view; others hold a different opinion. In his book "The Creation" the world view in question is concisely phrased by the author, P.W. Atkins, by means of the following words: "The deep structure of change is decay". And elsewhere he adds more elaborately: "Nevertheless, even though it may be concealed, the spring of all creation is decay, and every action is a more or less distant consequence of the natural tendency to corruption". Of course, in so far as a cosmic picture is intended such statements are to be considered speculations. Nonetheless they make their impression on those who get acquainted with the statistical approach to thermodynamics and try to understand what is meant by "entropy". And if, in more general terms, the "deep structure" of all ongoing change is the downward change which is "behind", the question may rightly be asked whether there is an escape from this speculation of far-away doomsday circumstances. Is there a way by means of which light may be shed on the artificiality of the picture? Is there a way to enhance the awareness of the particularity of the concept of change as used, a concept which is arbitrary in principle, invented by man and appropriate when dealing with certain circumstances but inappropriate when dealing with others? Is there a way - a direct way and not a sophisticated one - by means of which a reorientation may be brought about? In my opinion a reflection on the idea of substance is an unavoidable element when considering the problem which has been posed.

ON PERMANENCE

The first question now to be answered is what is precisely meant by the word 'substance'. If one has a look in an encyclopedia, one finds that 'substance' refers to the "essential nature" of things, which underlies the phenomena as they are observed. It refers to a kind of being which subsists by itself, and which may receive modifications without being itself a mode; that is, 'substance' is defined as the constituent material or matter in which accidents or attributes may inhere, thus making it into a particular "piece of substance". The term 'substance' may further be used as the general term indicating the "stuff" of which the world is made up, and in this connection the concept of substance is often considered equivalent to the concept of matter.

In physical instruction substance or matter - these words being used indiscriminately - is easily identified with a multitude of corpuscles, that is with molecules or atoms and with their constituents; ultimately, perhaps, it is identified with quarks, the new "queer" particles which have proved to be observable without being separable. Finally "matter" and "energy" may be related, and the concept of a quantum of mass compared to that of a quantum of energy. Now it may be said that the common sense concept of a corpuscle or particle is generated by , say, a picture of billiard-balls. Hence, if one tries to understand the second law of thermodynamics, the "entropy law", by means of a kinetic theory, it is generally a world of microscopic billiard-balls which provides the background of the problem to solve.

Which help can we expect from this setting, and which obstacles may arise and obstruct our efforts to obtain a solution? Clearly if empty space and time are filled with a wealth of mini billiard-balls, all moving, interacting and possibly "colliding", it is the idea of permanence, that is of persisting chaos, which is obtruding. Admittedly the particles are in a hectic movement, and there are many changes of configuration. But with respect to the particles the changes are external and can be described by means of functional dependences of the positions, velocities and other attributes of permanent entities of being. Conceptually it is classical point mechanics enlarged by electromagnetic and other field theories which provide the fundamental scheme needed when treating of the moving billiard-balls. And the continuity of the movement of the balls together with the permanence of the identity of each ball individually are expressive of a world of unchanging conditions; they are suggestive of a "perennial" philosophy of a material universe:

νόμῳ χροιή, νόμῳ γλυκύ, νόμῳ πικρόν·
ἐτεῇ δ' ἄτομα καὶ κενόν.

"For it is corpuscularity, it is truly atoms and empty space which make up the world, though at first sight it may be the sweetness or the bitterness of things which impress our senses"; the words, here rendered freely, are ascribed to Democritus, the father of atomism in Greek antiquity.

As a matter of fact a theory of moving particles may be considered outdated. Instead of presenting a "kinetic theory of gases", brushed up for the occasion, and devices of classical theory, one should consider atomic or molecular states of solid matter all defined by means of quantum mechanics. But with respect to science instruction the role of the newer developments in physical theory is secondary. Our education is far more dependent on scientific concepts which date from the 19th century, than on the conceptually sophisticated attainments of the present century. And even those who are highly skilled in the latest techniques may still find themselves philosophizing against a background defined by previous times.

ON CHANGE

"It is truly atoms and empty space which make up the world ..." according to Democritus. But atoms cannot be observed directly, and the phenomena, as they are, cannot be denied! The phenomena have to be "saved"; and the corresponding phrase "διασώζειν

τὰ φαινόμενα" came into use in order to express that full weight had to be given to what may be called the "appearance" of things. For "appearance" provides a persistent challenge. Clearly the "trace" of things which are observed, of things as we are aware of them, can be followed to what one considers to be their origin or source; the phenomenal thing may be "reduced" to what it possibly is "in essence". But for all that the role of appearance remains crucial, as it provides us with the challenge to explain a manifestation of change against a background of permanence, hypothetic always. Also Democritus was impressed by this state of affairs, and it was by the help of configurations of atoms that he attempted to explain things as they appear before our eyes. In his opinion patterns of causality - called " ἀνάγκη ", "mechanical necessity", in Greek antiquity - had to be such that the facts of appearance could be reproduced in corpuscular terminology. Scientifically this corpuscular "rock-bottom" of the world stood out most clearly in the 17th and 18th centuries; and it found its culmination in the well-known Laplacean statement, in which the world was compared to a clockwork enabling the scientist to calculate all events in the universe "ab initio", from the very beginning .

The 18th century ended with the proud statement of Laplace's which witnessed the religious conviction of an epoch. And because the conviction was firm, the 19th century was to become a period of strenuous conflict defying the believers in question. Two main conflicting points can be discerned.

(i) Already the 18th century knew about an expanding world and a time flowing in forward direction - "equably", according to Newton's scholium. But the idea of a cosmic clockwork and the hypothesis of a possible "big bang" in prehistoric times was not implied by physical theory. Consequently the direction of time flow - the so-called anisotropicity of time - remained a fact to be inferred from experience only. The laws of mechanics, and also of other theories, implied that any motion, any development going one way, might just as well go the other way. Hence an explosion may be reverted to become an implosion; and time, defined by a time-of-flight procedure, might be taken to flow either way. Thus the "arrow" of universal change had to be considered "contingent", that is "conditional", or "dependent" on something else; the direction in which universal change was taking place was not determined by "necessity", but coming by "chance", happening fortuitously possibly. Consequently, the hypothesis of a universal reversion of motion, of a reversion of the direction of time flow was not discarded a priori for reasons of absurdity.

(ii) This conflicting point gained additional weight when in the course of the 19th century new facts were brought to light suggesting the possibility of a biological evolution. And when it was attempted to explain the evolution as surmised in the biosphere by means of models, conceptual schemes taken from the realm of physics and chemistry, an unexpected problem posed itself. For a "process", as it was described in the realm of physics and chemistry by means of the concept of entropy, always led to a kind of "equilibrium", to a state of matter characterized by a minimum of complexity of form. On the other hand, in the realm of biology "process" as observed was such that an increase of complexity of form was a "normal" development. The increase in sophistication observed in the realm of biology

was something taking place "naturally", whereas the concept of entropy only enabled an explanation in which all increase in sophistication had to remain "marginal", had to be a "fluctuation" which would be damped in due time.

To many scientists of our days the conflicting points as sketched before have been solved, or will be solved along existing lines if the appropriate refinements are introduced. We all know the history of the Boltzmannian approach with its "paradoxes", its reformulation in terms of Gibbsian ensembles, pursued by means of ergodic theory, so-called "coarse graining" and other conceptual devices. It has enabled us to deal with the facts of appearance against a background of permanence; and still to-day it induces some people to repeat the Einsteinian remark that appearance is an illusion. Basically this point of view is an extrapolation to present times of the conceptual paradigm of the epoch of Enlightenment, viz. "rational mechanics", a paradigm which was considered to be "true", that is "fundamentally" and " a priori" "true" for all times.

REDUCTION AND EMERGENCE

But is this way of dealing with the facts of appearance satisfying? - It is a strange thing that this question is not often heard. - Well, it can hardly be satisfying! In my opinion, calling appearance an illusion should be considered a phantastic speculation.It is a vain "theoretical philosophy" if the hypothesis of an unchanging universe "behind" all phenomenal things is taken as the point of departure when considering the "facts" of experience. This postulate of what is called an "objective world" is an instance of that kind of metaphysics scientists have rightly claimed to be rejectable. Hence, the speculation in question is certainly not satisfying if viewed from the angle of "method". And it is not satisfying either if we keep in mind what may be considered the root of all scientific endeavour: to understand what happens in order to be able to cope with what is perceived as a threat to human existence, and in order to contrive tools and to invent artefacts for the sake of comfort. In this context 'human existence' is used as a primitive term, a term which is not in need of any further clarification. But explaining the facts of appearance by pointing to an unchanging universe "behind" them tacitly implies that the term 'human existence' is no longer considered primitive. If man is suggested to "escape" from what he observes and to "settle", to "establish" himself in a hypothetic world, his experience becomes "strange" to him. This means that the value of his experience is "robbed" from him, fiction taking its place; and that is why such a human being must be called an "alienated" being, a "displaced person" who is prevented from living in the place of his basic trust. Some decade ago in his "Le hasard et la nécessité", "Chance and necessity", J. Monod has done his utmost to make the state of affairs as sketched acceptable. What I consider unsatisfactory is declared by him to be "objective truth" imposed by a method which is "thoroughly" sound and rightly claiming our submission, a submission moreover requiring ascetism, a term which proves that Monod may not at all be satisfied himself.

But how has it come about that this phantastic speculation, this kind of a metaphysics which has gone the wrong way, could present itself as a necessity, as something inevitable? The answer to this question is, in my opinion, that the common sense notion of identity as applied to the idea of substance is the root of evil. For a piece of matter which entirely subsists by itself and consequently is not alterable "in essence", only enters into a relation with an other piece of matter if whatever is new in the configuration, which is established, remains accidental, remains an attribute of the pieces brought together; that is, the attribute in question is interpreted solely against the fundamental situation of two-pieces-being-joined but which are first of all two pieces still. This is what before has been called "reduction", namely a "reduction" of whatever there is to its so-called components, a relation between the components belonging to a category of a secondary kind. In contradistinction to this notion of "reduction", which is the outcome of a human attitude in which we pierce "beyond" the phenomenal thing to its hypothetic components, there is the notion of "emergence". For "emergent" is the qualification one uses if what is perceived is recognized as such, that is as something irreducible(!) to whatever components one may discern or substrata one may imagine. As will be remembered, if the notion of "reduction" is characterizing our attitude we pierce "beyond" structures to discover the particles, the "corpuscular entities" which have "combined" to "make" the structures.But if, on the other hand, the notion of "emergence" characterizes our attitude we will be inclined to accept a "structure" as an entity in its own right, as a "structural entity" which "comprises" "constituent" particles but which plays a part of its own. And if due weight is given to this attitude we call "illusion" what in Einsteinian times was named "objective truth", whereas what was called an "illusion" in previous times may turn out to possess the quality of "ultimate" fact. As a result the approach where the "trace" of things is followed to what things are considered "in essence" is valued again. The approach need not be entirely abandoned. But the term "in essence" has lost its meaning. The understanding of the organized interplay of atoms is important, and so is the concept of entropy applied to it. It may be a helpful representation of what happens - but the statement that everything is "just" the result of the interplay of atoms makes no sense; this extrapolation to open systems of a theorem which is valid for closed systems does not impose itself any more. And, as regards the attitude of the human investigator, his craving for certainty will have lost its obsessive character. The problem of entropy and of much that is connected with it may consequently be seen in a new light.

A NEW NOTION OF IDENTITY

The common sense notion of identity was considered, as I expressed it, "the root of evil". As regards physical science some developments, which have taken place in this century, have indicated the need for a revision of what is understood by "identity"; and the developments in question have adduced evidence of the reversed roles of "emergence" as compared to "reduction", and of "structural entity" as compared to "corpuscular entity". Without going into any detail I mention here the "breaking of symmetry" leading to the creation of new entities, so-called "dissipative structures", as investigated for instance by Prigogine's Brussels School, and the discovery of the quarks, the entities by means of which a final classification of elementary particles seems to be a possibility but which cannot be

considered particles themselves. Now, repeating a question asked before, is this "new" way of dealing with the facts of appearance satisfying? Do "structural entities" help us when explaining the facts, and what does procure us an attitude devoted to "emergence" instead of to "reduction"? The answer to the question is that paying attention to structural entities and to emergence does indeed help us, provided the "dynamics" of the new way of dealing with the facts is sufficiently discerned. That is, the process-character of emergence should never be lost out of sight! If a structure has been created and is considered - "received" - as a new entity, "reduction" will enter again if we absorb it into a new theory with new entities of being and their relations. Thus, the process-character of emergence vanishes - it "perishes" following the terminology of Whitehead's "Process and reality" -; and the place of "dynamics" is taken by "statics" again, a "statics" as of Laplace's though revised and more sophisticated. For as soon as a structural entity is definitely (!) described, the old common sense notion of identity is applicable. Over and against the old notion of identity, generated usually by moving billiard-balls, the notion of an identity-with-process character stands out. It is an identity which cannot be characterized by "being" solely, because it is "becoming" as well.

When making a concept of this kind of identity with process-character the organic world is apt to help us. Already a particular organism conveys something of the new kind of identity, namely an interweaving of the classical notions of (simple) "identity" and "process" which cannot be explained by a dissection. Still, the average organism is limited in its possible developments - although one may be astonished because of what biological evolution as we know it often demonstrates. The organism which may be the only one satisfying us in the end is the entity called "man". It may be the only example which is really satisfying because it will always provide us with the appropriate model for whatever we are able to imagine and to construct; clearly "man" only will procure us the final model of man! And, indeed, it is in this sense that I. Prigogine advocates the "breaking of symmetry", as observed by him, and the ensuing creation of "dissipative structures" as instantial steps of a cosmic process, where man is "at home" again instead of being "in the margin". The cosmic substance, the substance of the universe and its entities is not pictured as something amorphous, and the identity of an entity not as of rigid billiard-balls; on the contrary, it is to be pointed out that man himself is the final paragon. In my opinion, this is also why science may intrinsically be called an anthropomorphic enterprise. For whatever endeavour we may start, what effort we make to describe the world which is our environment, our attempt at a coherent description refers us back to where we have started: our own being, carrier of our knowledge and of our existential values. Man is a micro-cosmos, and the cosmos is macro-man. And it follows that the place of man is not in the perspective of science. Matters are reversed, for the place of science is found to be in the perspective carried by man!

When closing this paragraph I turn to Greek antiquity again, to a period when myth was valued still and when man and human character were not eliminated but pictured exemplified in gods and demi-gods. According to Pherecydes, a poet-philosopher who lived in the sixth century b.C. in the Cycladic island of Syros, the nature of cosmic reality could be expressed by the words of the following strophe:

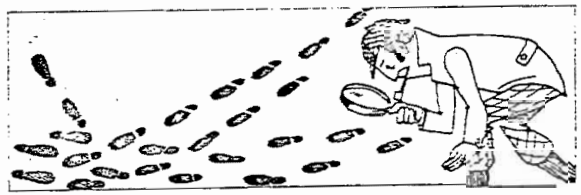
Ζάς μέν καί Χρόνος ἦσαν ἀεί καί Χθονίη·
Χθονίῃ δέ ὄνομα ἐγένετο Γῆ,
ἐπειδή αὐτῇ Ζάς γῆν γέρας δώσοι.

"Always there have been Zeus and Time and Matter-Earth; and the name 'Earth' came unto Matter-Earth, since Zeus endowed her with a body." Clearly in the Greek view of the cosmos a link is preserved between man-and-god and nature, a link which lies at the heart of all reality. For the earth becomes the earth-as-tilled by men and women; and the passing world receives its concepts from the hands of a supreme inhabitant, the human being.

We may be glad that the concept of 'entropy', which has become a theme for discussion for more than a century by-now, gives ample occasion to demonstrate that the "hard" sciences, which so often are totally dehumanizing, are "essentially" truly human, in the good things as well as in the bad. We need not be "alienated" beings or "displaced persons". We need not be "atomized" by science. For science is humanized. And we may be glad indeed that the sciences themselves thus remind us of a responsibility which is intrinsic and inalienable, and which requires strenous effort in times of imminent catastrophy.

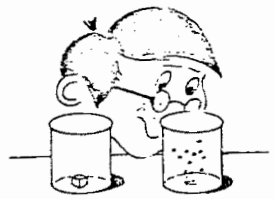
LITERATURE

For a survey of the problem of entropy the reader is referred to E. von Weizsäcker (ed.), "Offene Systeme I" (358 pgs), Ernst Klett Verlag Stuttgart (FRG) 1974 (ISBN 3-12-902410-7). The subtitle of the book is "Beiträge zur Zeitstruktur von Information, Entropie und Evolution"; in addition to a substantial introduction this book contains 9 contributions by different authors, each followed by a summary in English.



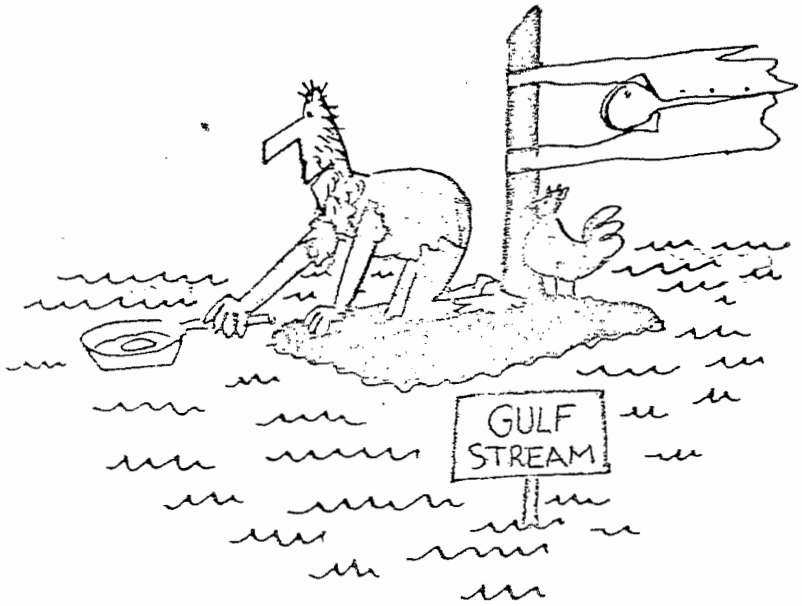
Miként a mesterdetektívnek a bűntény kideritéséhez, a természet titkainak feltárásához is az szükséges, hogy jól megfigyeld a környező világot.

Tégy egy pohárba hideg vizet, egy másik pohárba forró vizet! Mindegyikbe ejts egy-egy kockacukrot! Figyeld meg, mi történik a két kockacukorral! Azután gondosan fogalmazd meg, amit megfigyeltél!



"Fizika, grade 9" by E. Tóth in Hungary

Troisième difficulté : l'énergie doit correspondre à l'usage



Avec les milliards de calories du Gulf Stream...
allez vous faire cuire un œuf !

from "L'Energie ... c'est quoi?"
by L. Timbal-Duclaux

HARD ENERGY - SOFT ENERGY

Louis Timbal-Duclaux
Information and Communication Division
Department of Equipment, Electricité de France

All two often energy publications deal with the question in terms of quantity (there are so many millions of tons of oil, gas, uranium; we consume so much, etc.). Without denying the importance of this aspect, we would like to emphasize the other side of the energy problem, which is very often hidden: ~~that~~ of the quality of the different sources of energy. In practice, this aspects has proved just as important as the first.

I - A rational classification of energy sources according to their density

The word "energy" comes from two Greek words meaning "in" and "force" ("work"). As a starting definition, we can therefore describe energy as the property of a body to develop forces and furnish a certain amount of work.

Therefore, it can already be seen that the question of energy centres around two main points. Firstly, that of energy sources, i.e. "crude" forms of energy such as those found in nature (oil, gas, coal, solar radiation, water and wind power, etc.) And secondly, that of uses, i.e. work that it useful to main (lighting, cooking, heating, transporting, manufacturing goods, etc.)

Man must therefore master these "crude" sources, harness, organise, transport and store them with a view to using them in particular way. Herein lies the whole energy problem: a bridge must be built between the energy sources and their uses, able to transform these "crude" energy sources into effective energy.

The energy paradox: a shortage despite an abundance

There are, therefore, "crude" energy sources and "effective" energy sources. This distinction is fundamental in clarifying the current energy debate - all too often people speak of "energy" without specifying which of the two they are referring to. The result is a dialogue between deafs and endless discussions.

Let us take an example. A vulcanologue points out that beneath our feet the earth is overflowing with energy in the form of heat from the earth's core. This is known as geothermal energy. And he accuses the public authorities of ignoring this source in favour of others. Likewise, a physicist declares that billions of calories reach us every day from the sun. "We need only harness them", he says, "and all our energy problems will be solved and the world will be free from energy problems furthermore".

Other people maintain the contrary. "The sun and geothermics cannot solve our problems. At the most they can only furnish an almost negligible source of auxiliary energy."

This brings us to the heart of the energy paradox. On one hand, the earth is overflowing with energy, but on the other hand, man has lacked sufficient energy in the past and still does. The proof of this is the current energy crunch. It mainly stems from the fact that yesterday oil was abundant and cheap. In the 1970's it became scarcer and more expensive. Its price increased more than twentyfold from 1973 to 1979. And since 60% of the energy currently consumed throughout the world comes from hydrocarbons, considerable upheavals in the world economy resulted.
To clarify the current situation we will begin by examining the quality of the different energy sources.

A - ENERGY IN NATURE

(The twofold origin of energy: nuclear fusion and gravity

The world is full of energy; it surrounds us on all sides - a pebble that rolls, a plant that grows, an animal that runs, a fire that burns, myself thinking and writing. All these things involve energy transformations. Let us try to see the matter more clearly. Surely these different types of energy have a common source?

"Yes", the physicist will reply, "its source is twofold: nuclear fusion and gravity". If nuclear fission and geothermics, which come from the earth itself, and temporarily excluded, all the energy which exists comes from the sun. The primitive people who adored the sun were not far wrong. Without it, life would not exist on earth and the earth itself would not exist as a planet.

The sun, say the astrophysicists, is a gigantic thermonuclear reactor, an "uninterrupted H-bomb" which has been "exploding" since the beginning of time. At this very moment, at each second, billions of hydrogen atoms are being fused together to form a slightly heavier body called helium. In doing so, a small part of the matter as such disappears, to be transformed into a large quantity of energy which is radiated throughout the universe and received in part by our planet.

The sun is but a very small star amongst many others, but it is ours! All other reactions stem from this initial reaction. If it did not exist, none of the simple bodies that we know would exist - neither lead, nor copper, nor iron, nor oxygen, nor carbon, etc. - and with greater reasc complex bodies such as air, water, plants, animals, etc. And neither would the other sources of energy exist - oil, gas, coal, wood, water and wind power, etc.

But nuclear fusion would not be possible if matter did not possess a second fundamental property - gravity.

Without it, the universe would be made up of an imaginable mist of particles. For hydrogen atoms to exist and combine with each other, the particles of matter must be attracted to each other. It is this force hidden within the matter itself, which makes the world what it is.

It was Newton who first defined this fundamental law of the universe. "All bodies are attracted to each other in direct proportion to their mass, in inverse proportion to the square of their distance". (A law which, two centuries afterwards, was further developed by Einstein).

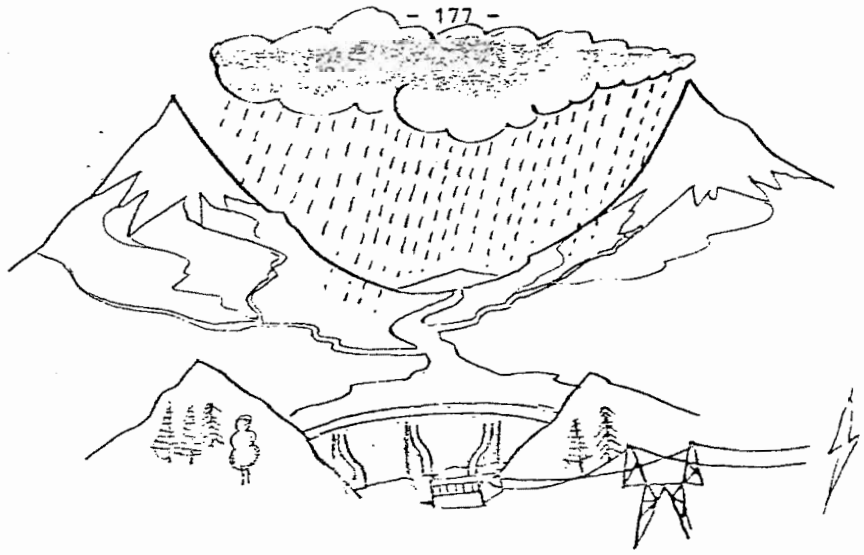
In brief, gravity introduces order into the universe. Through it, nuclear fusion is possible, the primordial source of energy from which all others follow. Seen from this fundamental viewpoint, even nuclear fission comes from fusion. And the day man succeeds in harnessing nuclear fusion, he will simply have reproduced on earth the harnessing of the sun.

From the sun to the main energy sources

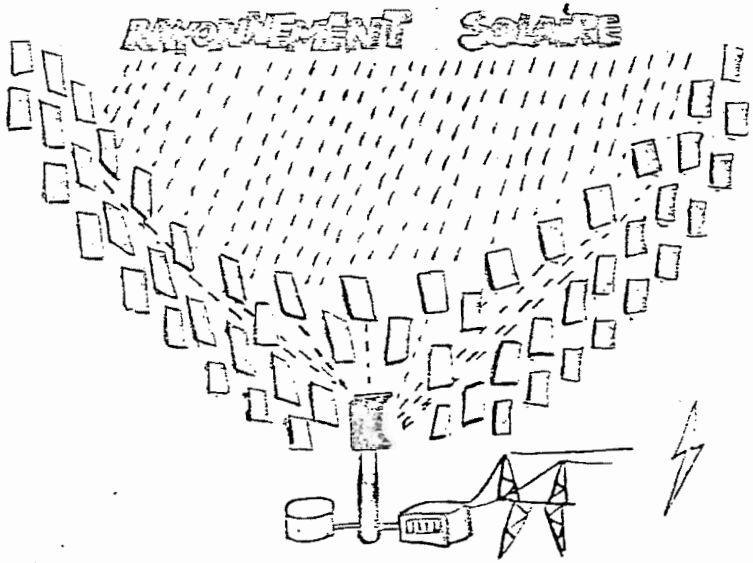
So to achieve a coherent view of the energy sources which exist thoughout the world we must start with solar radiation.

Solar radiation reaches the earth in the form of an uninterrupted flow of light and heat, which at any given point, varies according to the rotation of the earth - night and day, summer and winter, etc. Part of this energy causes water to evaporate and to condense in the form of clouds. The hot air rises while the cold air goes down.

From these movements of the atmosphere comes the wind, which produces, among other things, waves in the sea. The wind pushes the clouds which fall as rain. The rain is collected on the mountain slopes and forms water sources - streams then rivers which finally join the oceans. And the cycle continues indefinitely. The forces of gravity, together with the sun and moon, form tides. Under the effect of weight (i.e. gravity), water from rivers flows along, becomes



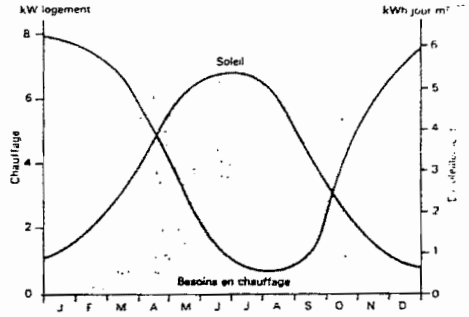
L'énergie hydraulique : une énergie de flux déjà captée et concentrée "gratuitement" par la nature.



L'énergie solaire : avec le rayonnement solaire, tout reste à faire.

from "L'energie ... c'est quoi?"
by L. Timbal-Duclaux

concentrated in valleys, and produces hydraulic energy. Plants capture the sun's rays. Thanks to the chlorophyll in their leaves, they use it to breathe and grow. This gigantic "plant factory" produces an abundant quantity of living matter known today as biomass. It supports both animal and human life.



By evidence, heating needs (for a home) are varying at the opposite of the intensity of the solar heat along the year.

To complete this summary, we must now go further and take a look at the inside of the earth. Accomplished without human invention, this work of harnessing and concentrating has now been carried on for millions of years. Slowly compressed, heated and concentrated, plant matter produces peat which forms shallow deposits. If we descend during further, we find coal which comes from the burying of forests during the primary era.

Oil and natural gas deposits are also found. These come from tiny sea animals or plants (plankton) buried and mineralised after upheavels of the earth produced during the secondary and tertiary eras.

How water deposits are also found at this level. They come from rain which filters through the earth and forms sheets of water. The water is heated as it flows down along the layers of earth. In fact, the centre of our planet is composed of a core of extremely hot matter (heat resulting from a nuclear phenonemon which is still poorly known). Then, thanks to other geological layers, this water rises

to the surface and can even emerge into the open air under the form of steam jets or hot springs. This is called geothermics.

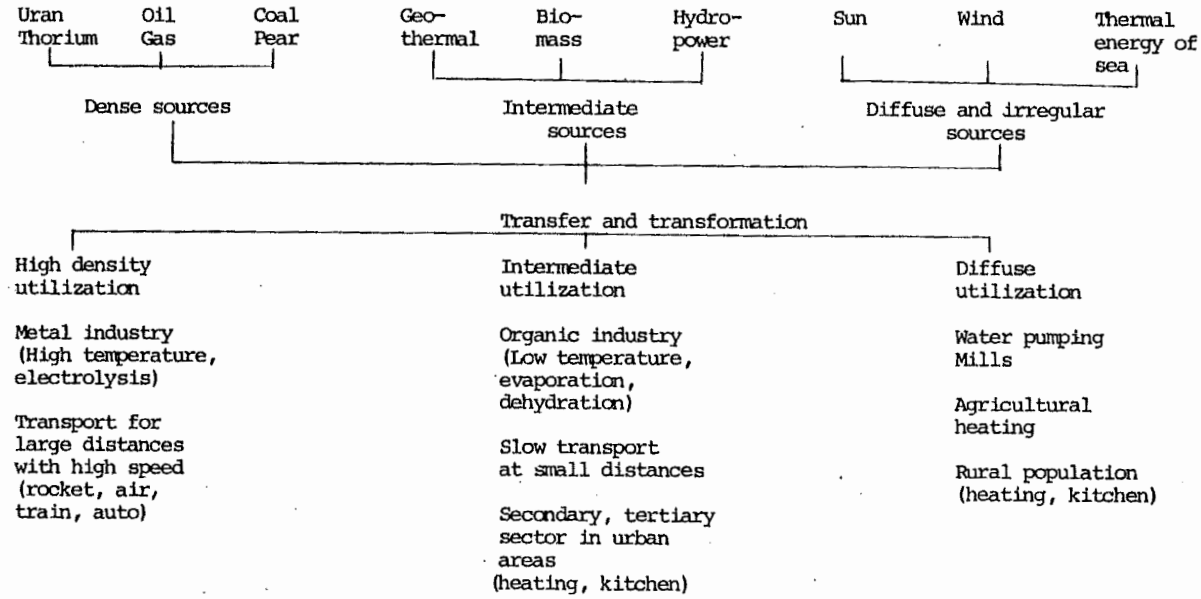
Finally very heavy metals are to be found - thorium and uranium. Correctly split within a reactor, they produce nuclear fission. Other lighter elements such as deuterium (a hydrogen isotope) or lithium can lead to nuclear fusion. (But at the moment it is not thought that this energy will be harnessed for civil use before the year 2020.)

The three energy stages: dense, intermediate and scattered

If we have described energy sources by starting at the top and working our way down, it is because nature does not do anything by chance - at the top are to be found the different energy flows and at the bottom, the stocks. Between the two are the semi-flow and semi-stocked energy sources. This classification corresponds to two basic characteristics of any type of energy - density and regularity.

We call energy density of a body the energy contained in a given volume. It is what the physicist calls the "volumic energy capacity". A body is considered energetically dense if it contains a lot of energy in a small volume. Inversely, a body is considered to be energetically scattered if it contains little energy in a large volume of matter. Thus, for example, liquid petroleum is denser than natural gas and flowing water is denser than the same flow of air.

Energy is considered to be regular if it occurs equally and continuously in time. Inversely, an irregular source of energy is cyclical (e.g. the sun) and/or intermittent (e.g. the wind) and, to an even greater extent, completely haphazard (e.g. a volcano).



Note: The effective use of any source is limited by the narrowest neck of the channel. A dense source can be used for any kind of utilization, but it is difficult to use a diffuse or irregular source with high density. As a matter of fact, dense sources give 85%, intermediate sources 15% of the energy consumption. The contribution of diffuse sources is negligible. Electricity is the polyvalent energy carrier.

The combination of the density and regularity of an energy source is closely linked to a third factor: its more or less renewable nature. Flows can be renewed, but not stocks.

A source of energy is considered renewable if it is reconstructed more or less instantaneously (e.g. the sun, wind, waves). It is considered semi-renewable if it is reconstructed over a moderate period of time (e.g. biomass, geothermics). It is not renewable if, once exhausted, it is completely finished and no longer exists on a human scale (e.g. fossil fuel).

These three characteristics are closely connected. In practice, it has been observed that the more a source of energy is dense and stored, the less it is renewable. Inversely, the more an energy source is scattered and irregular, the more it is renewable.

This gives the following classification:

Energy Sources	Stocks	Intermediate	Flow
density	high	moderate	low
regularity	high	moderate	low
renewable nature (on a human scale)	not renewable	semi-renewable	renewable
location	in the sub-soil	near the surface of the earth	in the atmosphere
main sources	uranium petroleum gas, coal and peat	geothermics biomass	energy from the sea, wind and sun

Dense and stored energy:

This type of energy is to be found within the earth's crust - peat, coal, natural gas and petroleum. It is primitively organic matter derived from the biomass (carbon and hydrogen-based), which came down from the surface and was gradually concentrated and mineralized during the different geological eras to form deposits. These fossils fuels are dense and can be stored and used almost directly by man. Their disadvantage is that they are not renewable.

A second category of dense energy comprises very heavy metals such as uranium or thorium that we will discuss later on.

Flow, scattered and intermittent energy sources:

Above the surface of the earth are to be found the flow energy sources: direct solar radiation, wind and waves. They are scattered, that is not very dense.

They are also cyclical and irregular: one moment the sun is shining, the next it is not; one moment the wind is blowing fiercely, the next it is not at all, and so on.

This type of energy is therefore difficult to transform into efficient energy. This is its main disadvantage. However, it has the advantage of being permanently renewed.

Semi-dense or intermediate energy sources:

These are to be found on the very surface of the earth - biomass, geothermics, hydraulic energy. In this case, nature has already begun its work of collection and concentration. They are both denser and more regular and are renewed at a moderate speed.

B - PUTTING ENERGIES TO WORK

Three problems to be solved

In practice, man must solve three problems when converting crude energy into efficient energy - location, time and quality.

Location: In order to be used, energy must be transported from the place where it is naturally found to the place where it is needed. This leads to problems of collection or extraction, transportation and distribution. For example, from an oil well to the petrol tank of my car; from a coal mine to my boiler; from the uranium mine to my electric plug; from the sun's rays to my hot water tap.

Time: At the same time, energy must also be available when it is needed, for the length of time required and in sufficient quantity. This leads to a series of problems concerning supply, regulation and storage equipment which could be solved, for example, by the woodshed in my barn, the tank of my car, the tank of fuel oil for my central heating system, the hot water tank of my solar heating system and the battery of my aerogenerator.

Another solution consists in permanently linking production to consumption by means of a network and producing energy as it is consumed. This is the case of network energies: hot water, steam, town gas, electricity. This does not totally eliminate the problem but simply displaces it. Certainly, interconnection of uses constitutes a vast "insurance" pool that benefits from the fact that consumers do not consume at the same time, save capital cost and increase reliability. But nevertheless "peaks" occur which require some storage facilities or over-equipment.

Quality: Quantity is not sufficient. The required quality of energy must also be available for a given use. For example, a block of a coal cannot feed the motor of my car, unless it is converted (a rather costly operation for the

time being), which consists in converting coal to synthetic gasoline. (This is what the Germans did during the last war, and what is now studied again, due to the rising price of oil.) Likewise, electricity supplied by a nuclear plant is incapable of fueling an aeroplane or a rocket unless it is used for water electrolysis which produces fuel hydrogen. Therefore, in practice, if the source conditions the usage, the usage also conditions the source. It is because we have so many motorcars and oil-fired residential central heating that we are so dependent on oil today.

The solution: A chain of converters

We call converters all the units, machines, equipment and plants which enable us to overcome these three problems, transforming "crude" energy into " harnessed" energy, that is ready to be used for a given purpose - lighting, heating, transport, communications, etc.

The energy chain is the series of converters which link an energy source to its ultimate use. For example, the oil chain extends from the desert derrick to my oil-fired boiler via converters such as oil pipelines, oil tankers, refineries, reservoirs and tank trucks to only mention the main links in the chain.

In the case of solar houses, all the equipment is grouped together in the same place. Problems concerning space are therefore reduced to a minimum but "time" now is the question.

It is when the sun is absent that we need heating! Not only must its scattered, haphazard radiation be collected and concentrated but various storage and control facilities provided to transfer the heat of the day to the night and if possible that of summer to winter.

As this is difficult, and in any case very expensive, a back-up heating system is practically needed for the coldest days and months of the year. This leads to a double investment and the unavoidable aid of a dense or semi-dense source of energy.

The overall energy system: restrictions of individual chains become more flexible through interconnections

The chain is as strong as its weakest link: A single converter need only be missing or be too expensive for a chain to be weakened or doomed to failure however abundant the source may be.

A few examples:

The Straits of Ormuz need only be closed and the West will be deprived of oil. Snow and ice can drive down the grid and deprive a whole area of electricity. The mining of coal, however abundant the source, is handicapped by the labour required; its weight and volume complicate transport. Natural gas is only easily marketable when compressed or liquified which are two different ways of making it more dense. All scattered energy sources are handicapped by their haphazard intermittent natures which requires heavy investments for harnessing, controlling and storing them.

On the other hand, by establishing bridges and connections between the different chains, new outlets become possible for each source, and, for the consumer, guarantees against price hikes and fuel shortages.

For example, although it is difficult to find direct outlets for coal today, we can try to get round the problem by sending it along different chains, for example that of natural gas by gasification, that of oil by liquifaction, and particularly that of electricity by using it in a thermal power plant.

In this respect, over the years, the electricity system has proved to be one of the main turntables of the energy system. All sources, or nearly all, can be used to make electricity - uranium, fossil fuel, biomass, geothermal steam, flowing water and even scattered energy sources (wind, sun

or sea, provided we are willing to pay the price).

Electricity can do everything, or nearly everything - provide heat, cold, motive power, lighting, transport, communication, and information. Infinitely divisible convenient and perfectly controllable, electricity, although it cannot be directly stored, wins the day with its incomparable qualities. As appropriate converters are developed, it continues to conquer new markets.

Electricity is particularly precious during the current period of energy system reshaping. Upstream sources can quickly be changed without needing to replace the downstream system i.e. either the network or consumer equipment.

Today, in France, four light bulbs out of 10 are fed by nuclear power, but no one is capable of saying which one. This is simply because, for the user, it is always the same carefully controlled electric current: 220 volts, 50 hertz.

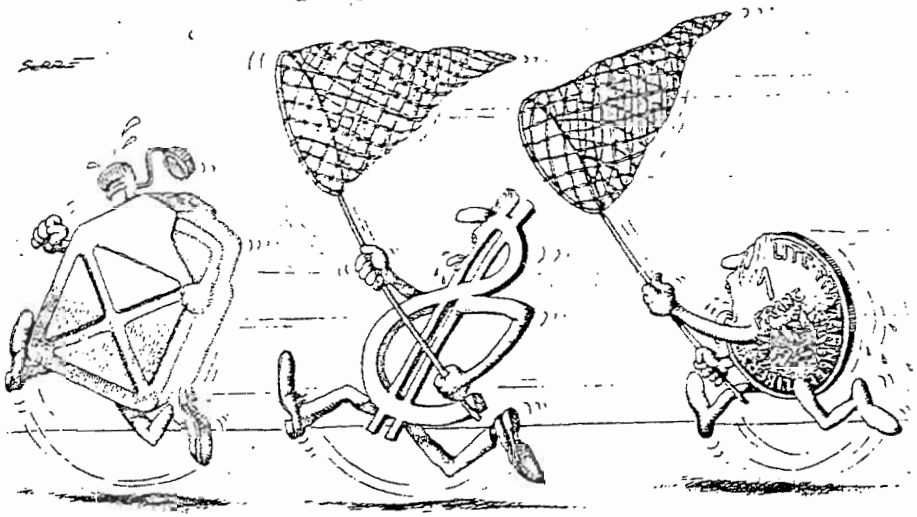
Therefore "energy" is less a problem of its source than of its transfer

We now understand the essence of the energy problem: contrary to what the public often believes, it is not a problem of sources but a problem of transferring those sources towards their ultimate uses.

In theory, the world is not short of energy - it abounds in it. We need only think of the enormous quantities of energy brought by volcanic eruptions, cyclones, tidal waves and other phenomena of this type! Had man succeeded in harnessing them, he would have been free from energy problems long ago. Unfortunately, that is not the case. What we call "energy sources" only represent a very small part of the energy which exists throughout the world - those that we know how to harness for our benefit according to current scientific and technical knowledge.

In this respect, all sources are not equal. Access to some is much easier than to others. In certain cases, nature

Energy savings? or oil? francs? currency savings?



has already carried out an important part of the work. But for others, everything, or nearly everything, remains to be done. But in any case, the work that Nature has not carried out for him "gratis", man must do it by devoting his efforts, time, materials, investments and even energy to do so.

The history of energy is that of scientific and technical progress

We can now understand why it is practically impossible to find a book devoted to the history of energy. Such works exist however, but under more general titles. They deal with the history of scientific and technical progress within the framework of the general evolution of humanity. And this is understandable, since progress in the field of energy is only one aspect, practically indissociable from the general advancement of human civilisation.

Taken as a whole, this evolution comprises two axes which are continuously intersecting:

1) For each source, regular progress (but by successive stages corresponding to the different innovations) leading to an increase in efficiency, i.e. an improvement in transfer efficiency;

2) Harnessing of more and more sources with the aim of greater diversification, each new source adding to the preceding ones without replacing them completely as time goes by.

History teaches us that man naturally began with the easiest sources to use, those at hand - biomass with the invention of fire and its derivatives and animal traction. These are what we called "intermediate" energy sources.

From the middle of our classification, it has gradually worked its way towards the outside i.e. to join the dense and scattered energy sources. Today it has reached both ends of the chain. On one hand the super dense fission (and tomorrow nuclear fusion), on the other hand, the super scattered i.e. solar radiation itself. These energy sources, which are opposed by their physical nature, have proved to be very complementary in their combined uses. By the way, they are the only energies that man can use for any length of time in space vessels: nuclear generators and photovoltaic panels.

Therefore, to the "all wood" fuel of neolithic times, in antiquity, man gradually added water and wind power, then in the 18th century, coal (with the shortage of wood), and in the 20th century, oil and gas. And recently, alternative energy sources - nuclear energy and more recently a return to flow and semi-flow energy sources. In the past, the economy was based on a single source. Now, it depend s upon ten or so sources, although very unequal in importance. In the current world energy situation, oil, gas and coal still represents some 84%, biomass and its derivatives some 10%, hydraulic energy 5%, nuclear energy 2% with the remainder

i.e. almost nothing, going to the so-called alternative energies. In fact, less than 20% of the energy currently consumed around the world is renewable or semi-renewable.

II - THE ORIGINALITY AND ROLE OF NUCLEAR ENERGY

In this vast panorama, how can we define nuclear energy? In two ways. First, we respect to other dense energy sources, i.e. fossil fuel and second, with respect to scattered and renewable energy sources.

Like fuels, uranium is a dense energy source but it differs from them in two ways. Firstly it is much denser and secondly it is of mineral and not organic origin. It belongs to the field of physics and not chemistry.

Physics versus chemistry: a super dense source of energy

Uranium is a metal. It is even one of the heaviest metal in nature, as can be see from its position at the end of the periodic table of elements. Although it varies according to the nuclear power system used, the energy produced by fission is approximately 10000, times greater than that obtained from the combustion of the same mass of matter.

This is easier to realize if you consider that a kilogram of uranium oxide fuel fed into a pressurized water reactor supplies as much energy as 8 tons of petroleum (without reprocessing).

For the public, this property is misleading. People imagine that nuclear power plants are enormous installations. This is true when you consider the volume of space they take up in the countryside. But what the public does not see is the much greater quantity of energy they produce. What counts, in fact, is not so much the size of the installation itself but the ratio between its size and the energy produced.

There the picture changes completely. Compared with the amount of material used (concrete, steel, etc.), the plant

is a miniature installation. A nuclear power plant such as Burgey in France (2nd in the world for its power), for example, produces with its five units the equivalent of 7 million tons of oil each year i.e. the value of the only Lacq gas field deposit in south-western France or the whole of the Lorraine bigger coal basin!

Few French people realize that in the year 1981 the first time in its history, nuclear power has become the leading source of domestic energy with 15.7 MtOE, as against hydraulic energy (15 MtOE) and coal (15.4 MtOE).

Another result of this miniaturization is the easiness of storage. All the uranium needed to operate all the French nuclear power plants for a year could easily be contained in a small suburban home. Another example: a single container of uranium from the Tricastin (Drome) enrichment plant contains as much potential energy as a 100 000 tons oil tanker. Six of these containers on a truck represent the equivalent of the largest super tankers which currently exist (600 000 tons).

A geographically scattered but fairly abundant metallic energy

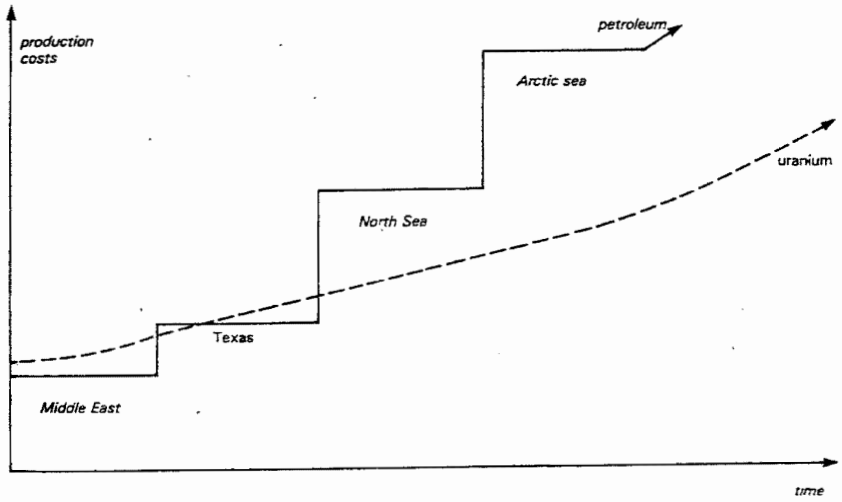
The metallic nature of uranium must also be stressed. It is in contrast to the organic origin of fuels (fossil plants and animals). These were formed, once and for ever, in very remote times. They are not renewable. At the most we can hope to discover new deposits which have escaped exploration and by improving techniques, to increase the recovery rate of known deposits and gradually to tap poorer deposits which have been disregarded up until now - tar sands and oil shales, for instance.

The fact remains that in all these cases a deposit constitutes a geological anomaly, rare point on the earth's crust. Their number remains dramatically limited. Exploration of the underground is sufficiently advanced in France for example to state with certainty that we are not sleeping above a new Middle East. We would know it if we were.

This is not the case for uranium and its fellows which are fairly abundant in the earth's crust in rocks of very different age and type. Certainly the uranium content of these deposits is not very high - roughly 3 to 4 grams per ton. But uranium also occurs as a possible by-product of gold production in South Africa, of shales in Sweden, of clay in the American west and of phosphates in Morocco. It can also be found in very small quantities in sea water (less than 2 micrograms per litre); and in lake and river spring water.

Expect for making yellow crystal, it does not have any use other than as an energy source, while oil gas and coal are valuable feedstock for carbo-chemistry and petro-chemistry.

In fact, because of their production costs, oil and uranium are mined in two different ways. The former takes places according to discontinued stages and the second follows a continuous curve.



In case of petroleum, enormous extremely accesible deposits (for example the Middle East) are firstly extracted. Reserves amount to billions of tons (these are the "billionaire" deposits). Then at a slightly higher level are to be found the "millionaire" deposits (for example Texas and Siberia). But the higher one goes the smaller the deposits are and/or the less and less accessible they are, such as those offshore at great depths or under polar ice.

Uranium production costs are not staggered in this way. The richest ores give way to slightly less rich ores without any sudden discontinuity. The mining cost curve rises slightly. Ratios of 1 to 20, such as those which exist between Middle East oil and that of the North Sea, are not to be found today.

Moreover, contrary to coal and oil exploration which date back more than a century, uranium prospecting only started in 1939. It has therefore heavily begun. By way for example we can mention the discovery of a 20 000 ton deposit in France in 1980 near Bordeaux. And no month goes by without hearing of the discovery of a new deposit somewhere in the world.

For historical reasons, this exploration, (apart from the Eastern bloc countries), has mainly been carried out in Anglo-Saxon countries (and their ex-colonies) up until now - U.S.A., Canada, Australia, the former Belgian Congo and South Africa. This is why they are currently the leading world producers. It could be said that, if petroleum is "muslim", uranium is "protestant": elsewhere, it has only just began seriously, not to mention thorium, a "fertile" metal which could be used in certain types of reactors.

In short, the only real limit to more intensive uranium mining is mainly a question of production costs as compared with those of other energy sources. If uranium has not been mined as much as it could have been, it is because up until now, the world economy was based on that wonder of nature - petroleum.

This "back gold" combines all the qualities of a

dense, liquid energy - easy extraction, transfer and transport, very convenient storage, high energy value. It has only one draw back - that of being very unequally distributed throughout the world and existing in limited quantities. Its supplies cannot last for ever.

The triumph of technology over physical resources

All these properties, which are derived from the density of uranium and its metallic character lead to one major consequence: the "converter" has come to supplant the source. Insofar as the economic and technical scarcity of the power plant (converter) now prevails over the physical scarcity of the source (uranium), the "source" of energy is no longer uranium, but the nuclear power plant.

This is why we say "nuclear energy" and not "uranium energy". This is why, justifiably, geography text books also consider in each country nuclear power plants (and not uranium mines) as a source of energy in the same way as oil wells. Without the nuclear power plant, in fact, uranium is worthless. Uranium only becomes a sources of energy with, in and through the power plant.

The first consequence of this is the fact that it is not the ore which is expensive, but the power plant. In the price per kilowatthour produced, the cost of the actual ore is only very slight - approximately 5% in a pressurized water reactor. And this is even more so in a fast neutron breeder which only consumes depleted uranium, a by-product of the enrichment of fuel from the former, a raw material unused until now which is waiting on the parking areas of the enrichment plants.

In other words, with nuclear power, humanity is entering a new phase in the conquest of energy. From now on, its production will depend much more on human work and intelligence than on resources to be found in the sub-soil. The whims of geology and prices will be a thing of the past.

The public is the victim of appearances when it talks of a possible embargo on uranium similar to those on petroleum. In reality, the balance of forces will be reversed. In one of the African states, for example, were to cease supplies, what would happen? Under current circumstances, it would be the one to suffer the most. Because firstly, it could do nothing with its uranium for lack of a power plant, and secondly, it would no longer be paid. The only solution would be to find another buyer, if one exists.

If we were to imagine that today, all of French energy supplies were shut off, we would only have a reverse of 3 months of oil in front of us, but 5 years uranium stock. The situation would be very different. Instead of having a gun at our head the way we do for oil, we would have five years in front of us to suit domestic production to our requirements.

With nuclear fusion, this would be even more marked (at least for reactor systems which do not rely on lithium). Here the physical resource is so widespread that it can be considered renewable. And this is where the two extremes come together - these super dense energies join the flow energies in their almost renewable character.

In both cases, the scarceness of the source fades in comparison with the scarity of human work: intelligence, technology and investments.

However there is a difference in size between nuclear energy and flow energies. For an equal quantity of energy produced, the latter requise much higher investments i.e. equipment and capital. This explains the enormous discrepency between current costs. While the nuclear kilowatthour is currently produced in France at a cost in the order of 10 to 20 centimes, that of a thermosolar power plant, such as Thémis, costs nearly 5 francs, and that of photovoltaic cells considerably more.

Conclusion: Limits and advantages of nuclear power in the diversification of energy

We now have a better idea of the advantages of nuclear power in achieving the energy diversification which has been made necessary by the oil crunch. We may also measure its limits, which consist in the capacity of each country to build the appropriate converter i.e. the power plant. Up until now, nuclear power was the privilege of industrially developed countries - those who possess both a good network capable distributing the electricity produced and sufficient technology and capital to be able to construct and operate a power plant.

The second limit, which concerns the development countries themselves, is that of public opinion. By misfortunate nuclear power first appeared to the public under the terrifying shape of the Hiroshima bomb, leaving its mark forever - at least up until the present. Crystalizing the anguishes of an era, it received much adverse publicity. But curiously, since the 1970's protests have shifted from the bomb to the power plant, a peaceful application par excellence. This is a serious problem which has been dealt with separately.

Whatever the case, the advantages of nuclear energy are obvious - its development bears the promise of long term escape from the unavoidable depletion of petroleum, giant macromolecules that Nature has taken millions of years to create and which are now more advantageous to use gradually as feedstock for the petrochemical industry.

The density of uranium, together with the flexibility of the electrical interconnection, is another advantage. Whereas the first industrial revolution, based on coal (later replaced by petroleum), lead to enormous concentrations of labour and serious pollution in the vicinity of mining deposits, the second, based on network electricity, enables, power to be produced in each region, close to its users, while at the same time benefitting from the advantages of a vast

pool which minimize the risks and reduce investments.

Making the most of things

It is therefore misleading to set up nuclear power in opposite to so called "alternative" sources of energy. Firstly, because nuclear power is currently the only authentically new source of energy, since the others are simply old sources which have been revived and renewed and secondly because, contrary to appearances, these flow energy sources are only "free" in the slogans.

Finally and, above all, whatever our political and social opinions may be, one major, alarming fact remains: in the year 2 000, there will be six billion people on this earth.

Except for a major catastrophe, (which no one could possibly want), if we are to clothe, feed, heat, light, instruct and employ six billion men intwenty years time, there is no choice left to us - we must harness all the energy sources that exist.

Knowing that they are not of equal value, neither by their form nor their source, in order to marke clear choices, we must compare the costs of the complete energy chains. And given the apathy which exists, in order to diversify our massive energy system, we must "get up early to arrive in time". In the words of Mr Hervé, French Minister of Energy, in September last "due to international tensions, each ton of oil saved is one more chance for peace".

> IN THEORY THE WORLD IS NOT SHORT OF ENERGY - IT ABOUNDS IN IT. CONTRARY TO WHAT THE PUBLIC OFTEN BELIEVES, IT IS NOT A PROBLEM OF SOURCES BUT A PROBLEM OF TRANSFERRING THOSE SOURCES TOWARDS THEIR ULTIMATE USES.
>
> Louis Timbal-Duclaux

HEAT

ENERGY IS THE ONLY LIFE AND IT IS FROM THE BODY; AND REASON IS BOUND OR OUTWARD CIRCUMFERENCE OF ENERGY. ENERGY IS ETERNAL DELIGHT.

William Blake

WITH ENERGY, ALL MATERIAL THINGS ARE POSSIBLE. WITHOUT IT, NONE ARE. GIVEN ENOUGH ENERGY, AS WELL AS TIME AND SCIENTIFIC AND INDUSTRIAL SKILLS TO USE IT WELL, WE CAN EXTRACT ALL OUR REQUIRED MINERALS AND TURN THEM INTO METALS AND MANUFACTURED GOODS. WE CAN TURN OIL AND GAS INTO PLASTICS, PURIFY WATER, MAKE FERTILISERS, RECYCLE SCRAP METALS, AND EVEN TURN CARBON COMPOUNDS INTO PROTEIN FOODS. HIGH-QUALITY ENERGY IS TRULY LIFE BLOOD OF MODERN SOCIETY.

Sir Alan Cottrell

Lord Shiva,
god of fire,
change,
revolution

THERMODYNAMICS FOR ANTIMATHEMATICIANS

Eric Rogers
Physics Department of Princeton University
Organizer for Nuffield O-Level Physics, London

I come as an old-fashioned physicist to take an old-fashionad approach to thermodynamics teaching, by reversible and irreversible engines.

A proverb, quoted by a stern uncle to a young person who changes his job many times: "A rolling stone gathers no moss" [1]. One wise young person asked "Why should a stone wish to gather moss?" We should ask here: "Why should average students who are not very happy with mathematics wish to learn thermodynamics?" Since we think that an understanding of thermodynamics is important for modern living, we can provide students with knowledge by giving simple explanations, but they will not learn well or keep their learning long unless we first make them wish to learn. We need to start by stimulating wish and interest and hope, by bribery with offers of surprising, rich, powerful results - like the tempting coloured pamphlets of travel agencies [2].

Thermodynamics is a very powerful game of scientific arguments, because it uses only two general assumptions, which seem safe from our experience. Then it makes predictions that apply to all materials, all engines, real or imagined. Here are some of those predictions:

A. "How hot is the Sun?" We can predict Stefan's Law, that flow of radiation energy is proportional to T^4 where T is the absolute temperature ($^{o}C+273$); and then we can use that to estimate the Sun's surface temperature, without having to send an impossible thermometer there by rocket!

B. " How efficient can you make steam engine [3]? Could you compel it to convert all its fuel's energy to useful mechanical energy, so that it is 100% efficient?"

Prediction: NEVER! Steam engines cannot be very efficient. There is a definite limit which you can calculate, quite apart from friction losses etc. Examples: A toy steam engine using steam from boiling water at 100°C in air at 20°C cannot be better than 21% efficient [4]. An engine with very hot vapour at 460°C to drive its turbine, and a river at 20°C for cooling, cannot be more than 60% efficient.

C. "A heat pump can heat your house with much more heat than you pay for. It is a refrigerator turned inside out".

D. "The ice skater's dream." (Here is a prediction that looks like a conjuring trick - a rabbit out of a hat.) Run an imaginary engine with a slush of ice and water in its cylinder and predict an effect that helps skaters! Put into the thermodynamic hat the following data:

melting point of ice = 0°C, which is 273°K.
energy to melt 1 kg of ice = 336 kJ.
density of water = 100 kg/m^3.
density of ice = 920 kg/m^3.
1 atmosphere pressure = 100 000 newtons/m^2.

And out comes the "rabbit", a number that tells us how much the melting point of ice drops for every atmosphere of extra pressure. That change provides the lubrication under the sharp edge of the skater's skate.

The two assumptions, Laws I and II. "Do you agree to them?"

Law I is a general statement of conservation energy, including thermal energy - which we previously called "heat" or "heat energy". If we include all forms of energy, the total does not change. Energy can move from one to another: but it neither disappears to nowhere nor arrives from nowhere. For our present purpose we may put Law I in a short form:

Law I: "We believe, from experimental measurements, that what we previously called 'heat' is a form of energy

which is exchanged with mechanical energy and other forms at a constant rate of exchange. If you agree [5] we can call it thermal energy and measure it in joules like the other forms."

(I have stated Law I here, familiar though it must be to readers, for an educational reason - see [5] - but Law II, which has a more complicated history, will have to be asserted - perhaps as suggested by early practical knowledge of real engines - in one or more forms that begin with it is impossible ... [6]. We shall use it in the following form in our game with wooden blocks, though the game can also be played with other forms.)

Law II: "It is impossible to make an engine pump heat up from cold to hot, continuously (cycle after cycle), without our supplying mechanical energy to help."

"We now take those two laws for granted as safe summaries of Nature and use them to lead to very powerful knowledge of engines".

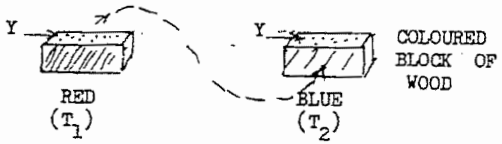
At this point, and in the ensuing argument, I show three big poster sketches which I have prepared, to save much wordy talk in teaching beginners. Picture 1 is displayed as soon as Carnot engine is mentioned; the labels on it summarize the events of the cycle; and a label for the mechanical energy output needs to be added, $W = H_1 - H_2$, when we have described the engine's perfection.

Picture II: displayed when Excelsior engine is mentioned.

Picture III: Carnot ideal refrigerator. Displayed when Excelsior and Carnot engines are to be compared. Point out that Carnot engine run backwards is an ideal refrigerator. (Then remove Picture I, keep II and III, and link them with an imaginary belt to show Excelsior's mechanical output being used to drive the Carnot refrigerator - so the net mechanical output is zero.)

In the teaching-argument that follows we avoid using the symbols > and < which so easily upset beginners and represent units of energy by wooden blocks (each of which

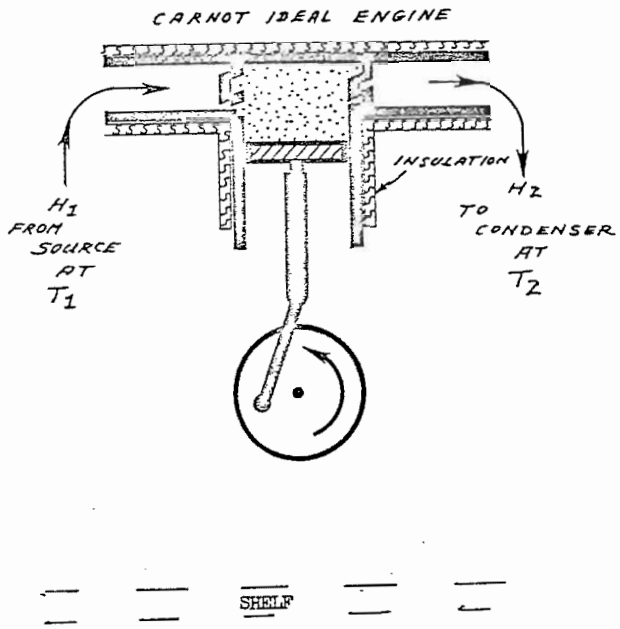
might be, say, 1 million joules). One face of each is painted red to show it is "high temperature" thermal energy from the furnace at T_1; the opposite face is blue to show "low temperature" thermal energy going to or from the cold river. (We point out that no real steam engine can work by taking in "heat" from a furnace and turning <u>all</u> of it to mechanical form - we could never get the steam out of the cylinder. It must throw away some "heat" to the cooling air or river. A "condenser" is essential, as early steam-engine designers found [7].) Sides of each block are painted yellow to represent the same amount of energy in (useful) mechanical form. We move the blocks and count them instead of using algebraic symbols.



<u>The Carnot engine</u>: (exhibit Picture I): "We imagine a simple, perfect ideal engine that

is frictionless
has perfect insulation ("ideal asbestos")
has perfectly conducting intake and output of "heat"
has balanced piston, moving very slowly ... etc.

It is only in our imagination, but the idea is useful because the engine is simple and reversible.



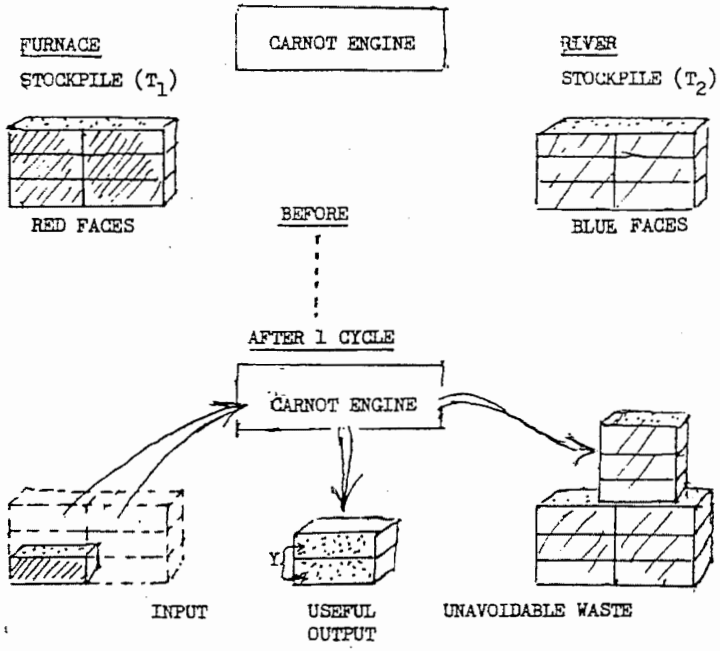
Picture 1

<u>A Carnot engine's balance-sheet, shown by energy blocks</u>

"Suppose our imaginary Carnot engine is one that takes 5 blocks of energy from the furnace (T_1) in each cycle, delivers 2 blocks of useful mechanical energy and throws away the remaining 3 blocks to the cool river (T_2). (5 = 3+2; our engine "obeys" Law I.) Then the engine would have an efficiency $\frac{\text{useful output}}{\text{input}} = \frac{2}{5}$ or 40 %.

In front of the Carnot engine picture install a self on which the coloured blocks of wood can be piled and can be moved along and turned to show colour changes.

From the furnace's stockpile, showing red faces for high temperature, (T_1), take 5 blocks to the Carnot's input; then move them farther along, turning 2 to show yellow for mechanical output and throwing away 3, turned blue for T_2.

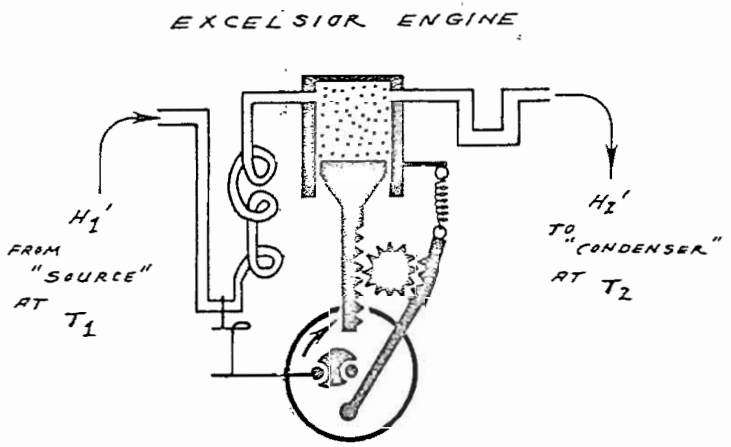


The powerful argument

"We chose to give our Carnot ideal engine an efficiency of 40%."

"We can show that, for the same furnace and river, no other engine can be more efficient. Suppose, for the moment, an enthusiastic inventor has brought us his Excelsior engine for which he claims greater efficiency, say 50%. Look at the

picture 2! You can see how impressive it is and how high his hopes! For 50 % efficiency it can take 4 red blocks from the furnace, deliver two useful blocks and throw away 2 to the river. Compare the two engines by making one drive the other backwards. You cannot tell whether the Excelsior can be run backwards, but we know the Carnot is reversible [8] . We let the Excelsior run forwards and drive the Carnot backwards as a Carnot refrigerator. We build our Carnot refrigerator to match the Excelsior's useful output, so that it uses the 2 blocks that the Excelsior delivers. See the picture of the two linked together. Then look at the energy-accounting in the box, and its verdict for Excelsior."

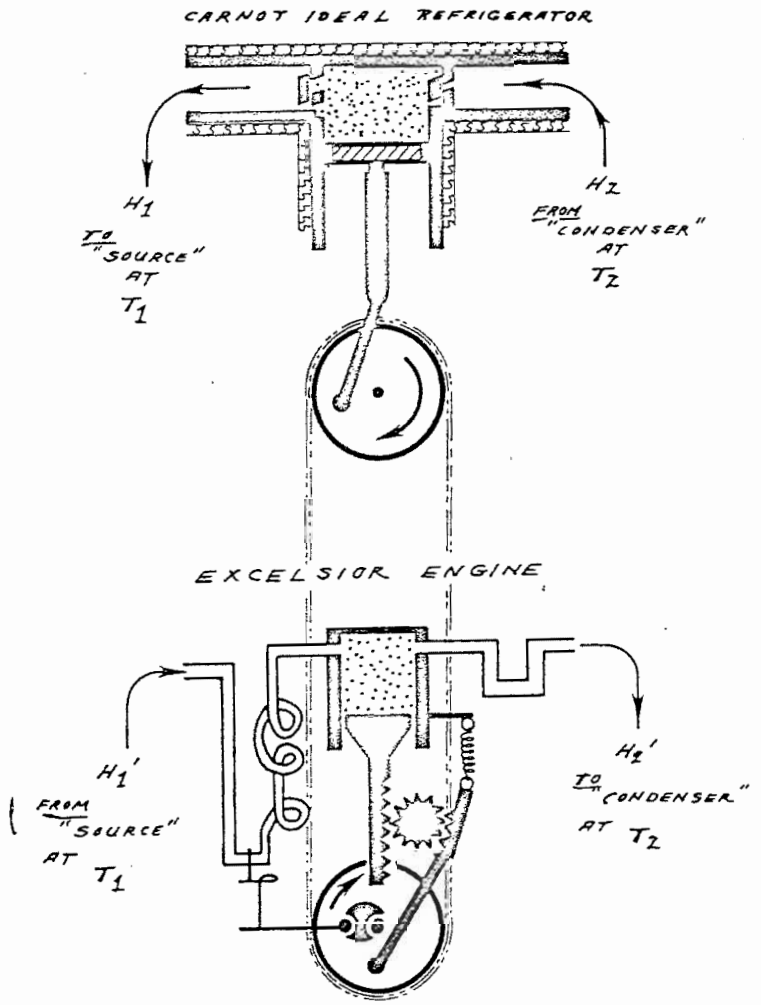


Picture 2.

Here is the energy-accounting for the two machines linked together (+ means taken-in by a machine, - means) given out), for one cycle, shown by moving wooden blocks, turning them to have the appropriate colour facing the students.

	THERMAL	MECHANICAL	THERMAL
	from/to furnace at T_1 (RED face)	(YELLOW face)	to/from river at T_2 (BLUE face)
EXCELSIOR ENGINE	+4	-2	-2
CARNOT REFRIGERATOR	-5	+2	+3
COMBINATION	-1	0	+1

The combination pumps one block of thermal energy from cold river io hot furnace in every cycle, without needing mechanical energy to help it. Since that disagrees with Law II, we believe it is possible to have an Excelsior engine more efficient than a Carnot engine. And, for the same T_1 AND T_2, one Carnot engine cannot be more efficient than another Carnot engine - they must all have the same efficiency whatever the working substances in their cylinders: steam, ice, helium, even radiation, even electrons... Here is a glimpse of the widespread predictions ahead of us.



Picture 3

The Carnot universal efficiency limit: " Thus, for two chosen temperatures, the Carnot engine sets a limit of efficiency which all other engines cannot beat, and all Carnot engines, however much they may differ in size or working substance, set the same limit - they all agree."

A new temperature scale (Kelvin)

"We think we know what length is by looking at it, and we believe we can measure lengths directly on some chosen scale. Most of us have similar informal beliefs about measuring weight, volume, etc. But our sense of hotness is vague (subjective), and when we try to make a scale of measurements - which we then call temperature - we find we have any number of materials and instruments and choices of formula to link the instrument's reading with temperature: many, many open choices, each yielding a scale 'true to itself', none more 'true' than others, though some more convenient. So the history of temperature-measurement is a strange one: air, mercury (tradition), alcohol, thermoelectric e.m.f., pressure of gas sample (clumsy, precise, the scales of many gases seem to agree closely - a temptation to optimists to say 'we have got there at least'!)" [9]

"A century ago Lord Kelvin suggested one more scheme: take the heat input H_1 and heat thrown away H_2 by an ideal Carnot engine to define the temperatures of 'furnace' and 'river' in the form

$$\frac{T_1}{T_2} = \frac{H_1}{H_2} \ .$$

Since the efficiency of the engine is

$$\frac{\text{(Mechanical output)}}{\text{(Thermal energy input)}} = \frac{\text{(Thermal energy input)}}{\text{(Thermal energy input)}}$$ and that is

$(H_1 - H_2)/H_1$ which is same as $1-(H_2/H_1)$ he certainly had a temperature scale that would be the same for all Carnot engines. Why did he suggest it? He was not just another rash optimist ('At last we ...'). He wanted to put many different materials into Carnot engines and make astounding, useful predictions."

Predictions?

From then on we can make predictions in the traditional way. How many we can give, of those in the tempting bribery at the beginning of this paper, must depend on the skills and interests of our students.

So I leave them for colleagues to try. Only one of those promises seems hopeless for non-mathematicians: Stefan's Law. But we can avoid the integration to logs, as follows:

As preparation, ask about errors in the calculated area of a square. "If you make an error of 1% in measuring the side of a square, what will be your error in the area? If necessary, work it out in an arithmetical example to show it will be almost 2%. That for of a cube of volume $(\text{side})^3$, 3%. Then if you find that

$$\frac{\text{small change of radiation flow}}{\text{radiation flow}} = 4 \ \frac{\text{small change of T}}{\text{T}}$$

you may suspect that:

radiation flow is proportional to T^4."

Disaster threatens

But, all predictions use Kelvin temperature scale. What thermometer do we have for measurements on that scale? Are we just floating in a theoretical dream?

For many students we should just say "Fortunately, a gas thermometer filled with helium at constant volume gives that scale very nearly, if we use pressure measurements".

For others, more inquisitive, I offer the following argument to link the two scales. It is <u>not</u> the traditional clean proof, that involves pV . It is <u>not</u> sound, but it suggests some support. Students will need to know that (pressure) x (small change of volume) measures mechanical energy; and therefore on a pV diagram certain area will measure mechanical output or input.

Connection between Kelvin scale (T) and constant-volume helium scale (θ)

Enclose some helium in a large metal bulb, thus keeping it at constant volume. Connect the bulb by a very narrow pipe to a pressure gauge, whose readings we take as "helium temperatures" (θ). Also put some helium in an engine which performs the cycle shown, that is:

A_1B_1 (isothermal) helium expands at constant temp T_1.

B_1B_2 at constant volume take away thermal energy and store that energy in a "heat park" [10].

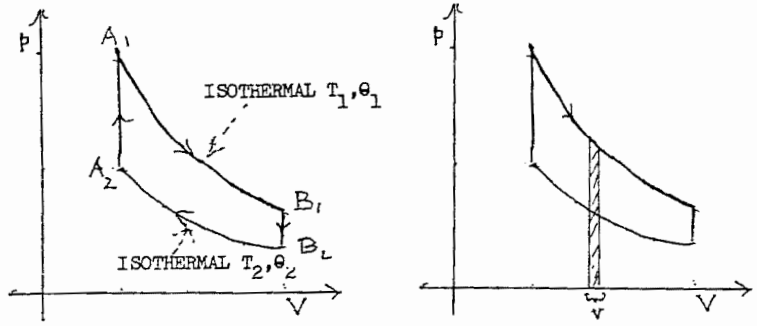
B_2A_1 (isothermal) helium constracts at temperature T_2.

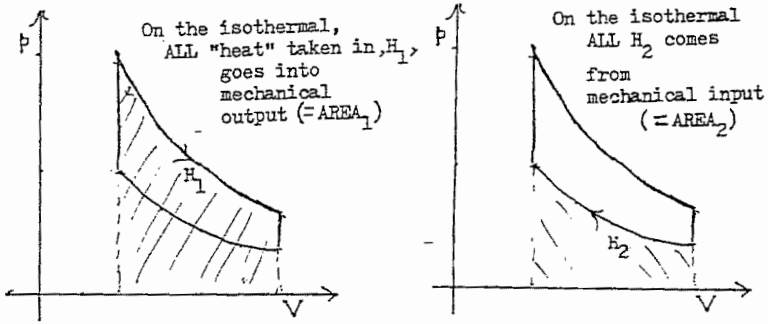
A_2A_1 at constant pressure restore the energy from the "heat park" at constant volume.

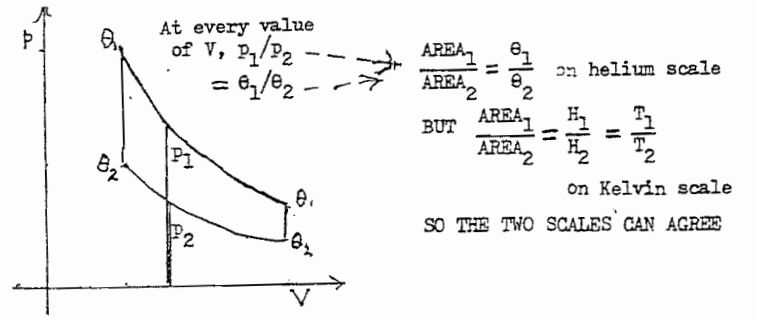
On the p-V diagram for the engine look at the pillar of small width v. Its area is pv, and that tells us the mechanical energy delivered as volume increases by v at

temperature T_1. Add up all such pillars for the whole change from A_1 to B_1. That shaded area is the mechanical energy delivered in the expansion A_1B_1. The shaded area below B_2A_2 gives the mechanical energy that must be supplied for the change.

The argument is shown by the small pV diagrams.







Notes

[1] Hungary has a similar proverb: "Görgő kövön nem nő moha".

[2] Young people desire power. If we can show them that thermodynamics is very powerful, they may treasure that knowledge - in contrast with the short life of things memorized for discipline, in the vain hope that such training will make them more scientific. In writing this paper, I sometimes give what I would say to young students. Where it is easy, I put such remarks in single quotation marks ("and"). Since this belongs to an educational seminar, I trust that physicist readers will not mistake those remarks for unnecessary talking-down to experts.

[3] Every school should have a working toy steam engine. Those who have tried running one in class - as a Nuffield O-level physics - have found it surprisingly fruitful.

[4] These theoretical ("Carnot engine") limits to efficiency are, of course far higher than the overall values attained in practice. A toy would be lucky to have 10%. And the big power-station engine quoted reaches only 30%. At 460°C steam is a gas, likely to corrode steel. A power station in Hartford U.S.A. has used mercury vapour at that temperature. The mercury is still fairly hot at exit so it is used to generate steam for a second stage.

[5] In teaching physics most of us find that we are driven to present some "general principles" by pure assertion either to save time or from a genuine need to avoid a long discussion of the nature of postulates. For beginners, I am content to share with Newton the conservation of mass and with Coloumb the conservation of charge, and just say that we take each of those for granted. Beginners consider they know what each of those things are like, mass and

charge, so at least it is clear what we are assuming. But conservation of energy is more complicated, less familiar for beginners - consider its slow adolescence through the nineteenth century. I am old-fashioned, and in teaching physics (*) I will not teach that principle solely by assertion; not say it's obvious, or treat it as a message from Heaven, or worst of all deceive students by claiming as proof "you cannot get something for nothing". We cannot prove it but we can give students a strong sense of its validity by showing them the stream of experimental knowledge that led towards it. We should show a varied selection of what were called in the Seminar "Joule experiments". (See, for example, "physics for the Inquiring Mind", Eric Rogers: pages 390-393 for descriptions of energy forms, and pages 436 to 441 for discussion of conservation.)

(*) I consider that we owe beginners in learning physics some examples of experimental support before we ask them whether they accept general conservation in the form of Law I. But the teaching in each science must make economies - or there will be overcrowding and indigestion and the simplicity of knowledge will be concealed. So good teaching in each science borrows from other sciences big blocks of knowledge, ready finished, often in a simplified form which the original owners would not approve even in their elementary classes. In his elementary teaching, a physicist borrows from chemistry simplified statements such as: "water is H_2O" (without mentioning hydronium); molecules of hydrogen and chlorine each have two atoms, diatomic, (without mentioning the delightful argument in elementary chemical theory to suggest that from gas volumes). An engineer borrows the physical view of energy-conservation by simply taking the First Law for granted. Such economical borrowings are necessary and forgivable, but taking energy-conservation for granted, ex cathedra, in the teaching of physics itself seems me unfair to the good name of science.

[6] "It is impossible ..." Thirty five years ago Sir Edmund Whittaker suggested that the whole of physics could be derived from certain Postulates of Importance, which recognise things which it is not possible to do. He wrote: "A postulate of importance is not the direct result of an experiment, or of any finite number of experiments; it does not mention any measurement or any numerical relation or analytic equation; it is the assertion of a conviction that all attempts to do a certain thing, however made, are bound to fail. We must therefore distinguish it, on the one hand, from an experimental fact: and ..., on the other hand from the statements of Pure Mathematics, which do not depend in any way on experience, but are necessiated by the structure of the human mind ..." The two laws of thermodynamics are excellent examples. Try expressing some other parts of physics in that way: relativity, electrodynamics, exclusion principle, uncertainty principle. If you wish to see Whittaker's versions, see his book "From Euclid to Eddington" (1949).

[7] I wish we could show pictures of the managers of darly steam engines pouring buckets of cold water on the cylinders to keep the engines running.

[8] P.W.Bridgman remarked that when we describe a procedure by a closed cycle on a pv diagram, we imply that it is reversible.

[9] Some modern physicists will say: "oh, but we now know that temperature is measured by average kinetic energy of gas molecules... so, in practice a constant volume gas thermometer will suffice. "Yes, but they too are still just making their choice.

[10] The "heat park" is the weak point - its behaviour will hardly bear proper investigation. But, as I am desperate to give some flavour of support, I use it claiming that although unsound it is not vicious. (Reflect that the specific heat of helium is independent of temperature.)

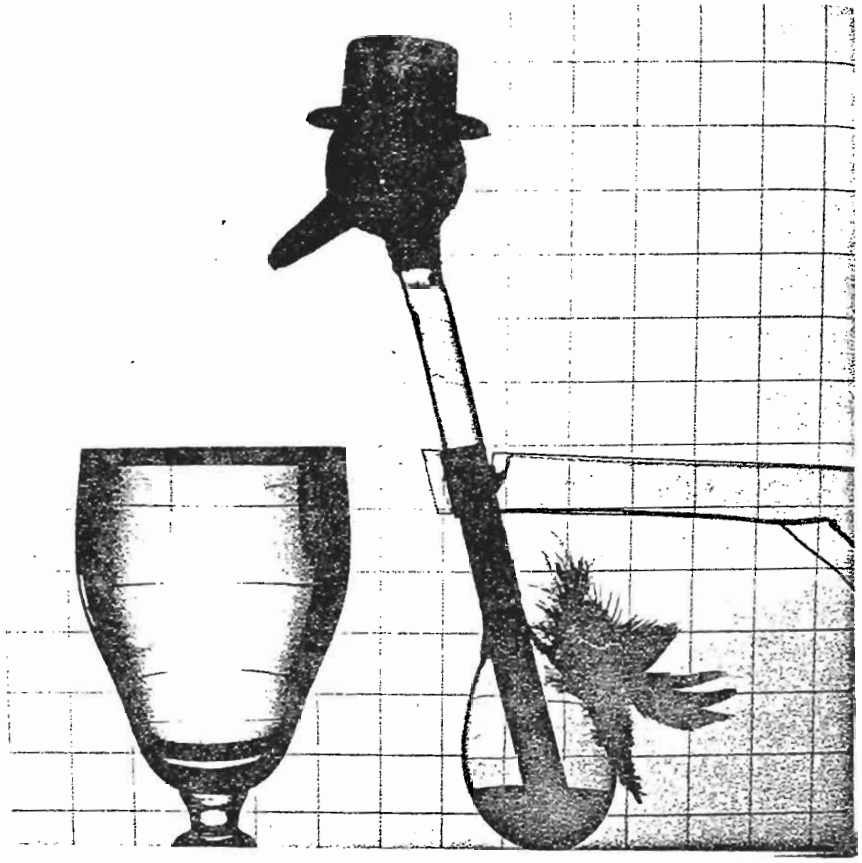
THE THERMODYNAMICS OF A "DRINKING" DUCK

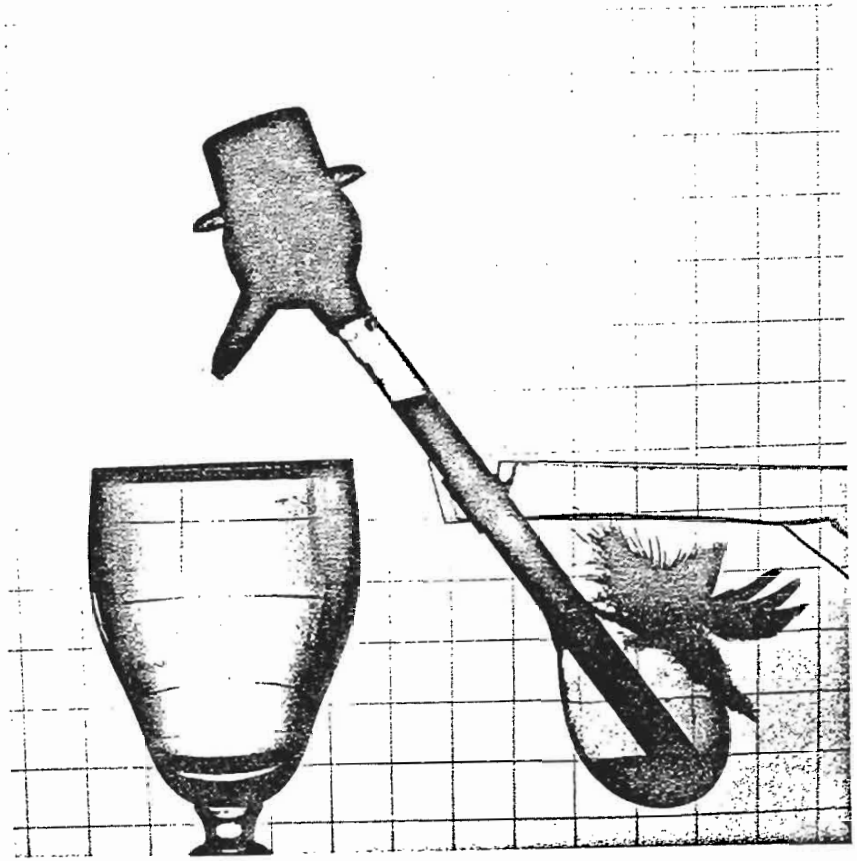
P. E. Richmond, University of Southampton

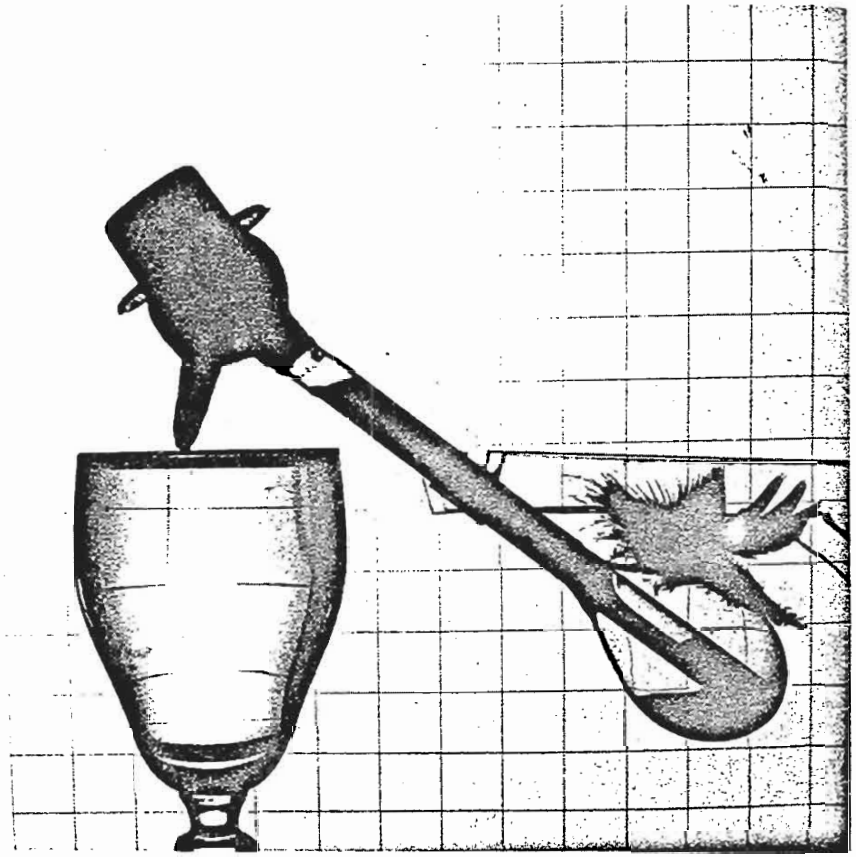
The 'drinking duck', sometimes called a 'goofy bird' or 'happy bird', is a moving model often used to attract attention in souvenir shops or as a talking point in an office or home. It is a simple heat engine and merits serious consideration as a source of study at many different levels in schools and colleges. The duck is made of glass and consists of two reservoirs connected by an internal tube (fig. 1). The lower reservoir (the body) is filled with a volatile liquid and the upper reservoir (the head) is covered with absorbent material. To start the duck in motion the head is immersed in water for a few seconds and the duck is placed on its stand. After a few moments' delay it tips over, its beak 'drinks' water in the glass, it recovers its vertical position and oscillates to and fro on its bearings until it tips again.

The Mechanics of the Duck

Before looking more closely at the thermodynamics it is necessary to understand the mechanics of the moving system. The construction is simple though ingenious and the model can be purchased for less than £1. The lower bulb (the body) contains a liquid with a boiling point near room temperature. This ensures that only small excess pressures arise between the duck and its surroundings and no danger is caused. Commercially produced ducks use methylene chloride or freon (trichloromonofluoromethane) to which is added a suitable dye. These liquids are non-flammable and non-toxic and are used in refrigerators which also depend upon the easy vaporisation and liquefaction of the fluids. The body and the head are at different temperatures and the liquid has a different vapour pressure in the two places. It is this difference which drives the







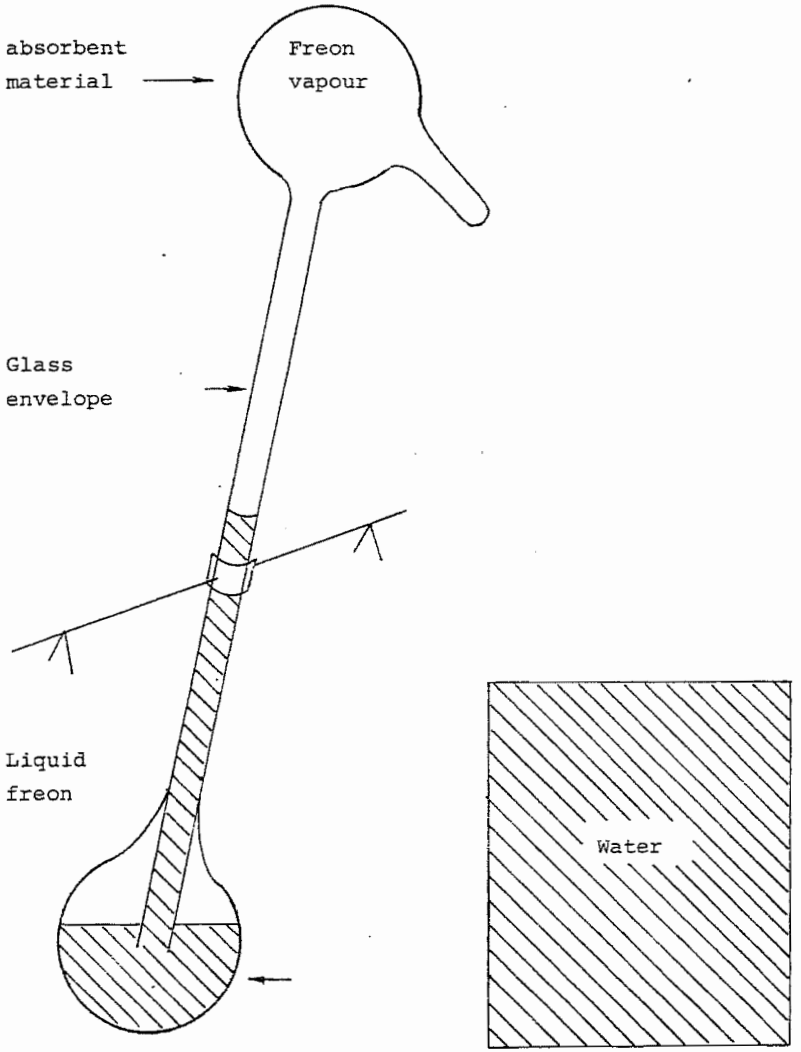


Figure 1.
Construction of the drinking duck

model. The pressure difference causes liquid to rise up the central tube towards the head. It gains potential energy and offers the promise of useful work. The duck when operating oscillates to and fro quite vigorously but the power is low. The centre of gravity of the moving system never moves more than a few millimetres above or below the supporting axis. A small vertical displacement of the centre of gravity above the supports causes the system to become unstable and the duck topples over. The head is stopped by the edge of the glass from which it absorbs moisture or by stops built into the stand. As it does so the liquid level in the body drops below the end of the central tube, liquid runs out into the body and a bubble of warm vapour rises to the head (this exchange is central to the thermal cycle and is considered in detail below). The net effect is to restore mass to the body and the centre of gravity to a point below the support. There is a restoring torque, the duck swings upright and oscillates about a vertical position until the liquid rises again in the tube.

The potential power of the engine can be calculated by timing the rate of rise of the freon in the tube. Not all of this power could ever be available externally since some is used in the thermal cycle during the interchange of liquid and vapour. However, upper limits to the possible power output of a 'duck-engine' are calculated as follows:

Density of freon = 1.6 g cm^{-3}

Diameter of tube d = 8 mm	Room	Sunlight	Fan-cooled
Mean height liquid rises	25 mm	20 mm	60 mm
Time for 10 oscillations	610 s	70 s	114 s
Number of oscillations per second	.016	.143	.088
Height liquid is raised per second	0.4 mm	2.86 mm	1.76 mm
Mass of the liquid	32×10^{-6}kg	41×10^{-6}kg	233×10^{-6}kg
Power (mgh)	0.013×10^{-6}W	0.25×10^{-6}W	0.68×10^{-6}W

This is small indeed and unlikely to provide useful work.

The Laws of Thermodynamics

The reason for the duck's popularity among the public is that it seems to go on drinking for as long as water is available. A reason for its interest to the scientific community is the same but stated in different terms: how does it relate to the laws of thermodynamics? At first sight it seems to be a perpetual motion machine, running continuously without an external energy source. Certainly there is no fuel supply in the usual sense. A few moments' consideration leads to the conclusion that the energy to drive the engine must come from the surrounding air. The first law of thermodynamics is not contravened. There remains however the second law stated by Kelvin in 1851 as 'It is impossible, by means of inanimate material agency, to derive (continuous) mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects' or in an equivalent form (the Clausius statement) 'It is impossible to construct a continuously acting engine that will deliver mechanical work derived purely from the cooling of a single heat reservoir, no heat being given out to a reservoir at a lower temperature.

The atmosphere is a single heat reservoir but the duck seems to create, of itself, a temperature difference between its two ends. This then drives the duck around its cycle.

To explain this anomaly it is best to distinguish clearly between two thermodynamic cycles. One maintains the temperature difference between the head and the body and supplies energy and the other is a closed system operating within the glass envelope of the duck. The first is an open system, the second is closed, depending on the first to create conditions under which it can operate.

Considering first the system which generates the temperature difference. This relies on evaporation of water from the absorbent material covering

the head. Every schoolboy knows that evaporation produces cooling! In our case the energy to evaporate the water is derived in part from the vapour in the head of the duck. The water vapour must be removed to allow more to evaporate and this is done by air currents in the room. If the system is confined by putting a bell-jar over the duck and its glass of water then it ceases to move in just a few minutes. The air under the bell-jar becomes saturated, water ceases to evaporate from the head and the temperature difference disappears. If a room containing a working duck were hermetically sealed then, given time, that duck too would stop moving. As in all discussions in thermodynamics it is essential to recognize the system in which events occur. A duck operating in a ventilated room is drawing its energy from the air in the room which is continuously heated by an outside source, maybe a central heating boiler or the sun. The temperature difference between parts of the duck is maintained by the removal of water vapour by the air in the room which must itself be dried or changed if motion is to be maintained. The system providing the energy and the correct conditions is a large one extending from the duck to the room and beyond.

The Vapour Pressure Engine

The duck is a heat engine comprising (a) a hot reservoir (the body) (b) a cold reservoir (the head) (c) a piston (the column of liquid) (d) a load (the weight of the column of liquid raised) and (e) a working fluid. The last of these is only a tiny fraction of the freon present inside the duck. A small mass of liquid is vaporised and liquefied during each cycle, most of the liquid freon serves only as a reservoir at comparatively high temperature and the freon vapour as a cooler reservoir.

The working cycle involves the vaporisation of liquid at very nearly

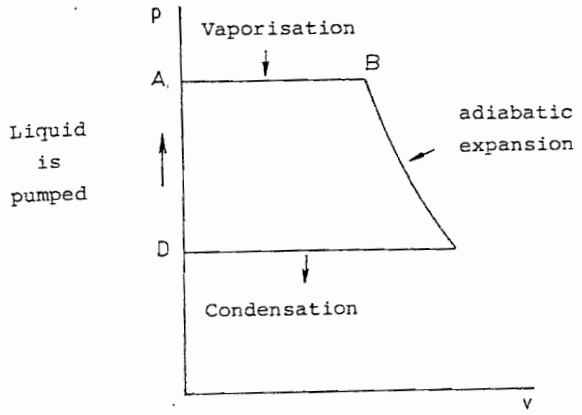


Figure 2. The Rankine Cycle

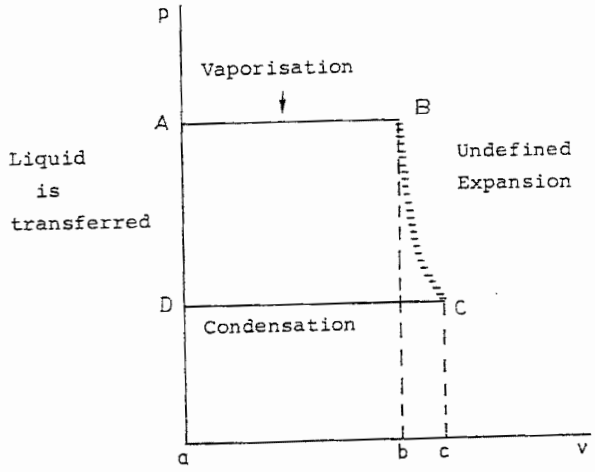


Figure 3. The Vapor Pressure Cycle

constant pressure with consequent increase in volume and the doing of work. Condensation follows and then the exchange of cold liquid from the central column and warm vapour from the body. The cycle of the duck is difficult to describe in detail because the different stages are not separated in time; they overlap and different stages take place simultaneously. In describing the cycle it will be assumed that changes take place sequentially. This is accepted practice in textbooks and is one of the reasons why theoretical discussions of common engine cycles such as those of the internal combustion engine (the Otto cycle) or a hot air engine (the Stirling cycle) produce pv diagrams very different from those of an indicator fixed to a real engine. Unfortunately it is not possible to probe conditions inside the parts of a 'drinking duck' and the pressures and volumes at different stages of a genuine cycle cannot be measured. A theoretical discussion will have to do.

The cycle followed by the freon in a duck is similar to that followed by steam in a steam engine. In both, the working fluid changes phase twice and it is helpful in understanding the operation of the duck to look at the Rankine cycle (fig. 2) which an idealised steam engine follows and the cycle followed by the duck (fig. 3).

In a steam engine water in a boiler at point A vaporises at constant pressure from A to B. The steam then expands in the cylinder adiabatically from B to C and external work is done. There it enters a condenser and becomes liquid (C to D). Finally the condensed water is pumped mechanically from D to A or more often, is dumped and replaced by fresh water at A giving the same result. The net result is external work proportional to area ABCD. The cycle is then repeated. In the duck freon vaporises in the body at its saturated vapour pressure and the increase in volume from A to B at constant pressure means work is done by the fluid proportional to the area ABda.

In the duck changes take place slowly in uninsulated containers; adiabatic conditions are not present so from B to C the vapour expands in an indeterminate fashion. Matters are made more complex by the fact that as liquid vaporises in the body so vapour liquefies in the head. Between B and C vapour is expanding in the body and helping to raise the level in the central tube. At the same time vapour is starting to condense in the head. Between B and C the action moves from body to head, equivalent to a transfer of fluid into a condenser. The functional relationship between p and v is unknown and so it is not possible to trace accurately the line from B to C on the vapour pressure cycle of the duck. It will however be steeper than that of the Rankine cycle and less work will be available. From C to D it is the vapour in the head which is active. Liquid condenses and work is done by the vapour proportional to the area CDac. In the Rankine cycle water is pumped from D to A. In the vapour pressure cycle of the duck cooled liquid from the central tube is driven by gravity back to the hot reservoir (the body) and the work done in this process is lost to the duck just as the energy of the pumps in a steam engine reduces net output. At the same time a bubble of warm vapour is transferred to the cold reservoir (the head). Immediately vaporisation and expansion recur in the body and condensation and contraction recur in the head taking the duck round its cycle again.

In the model duck external work is done only against friction but thermodynamically there is no reason why excess power should not be available. It will be proportional to the area ABCD. To calculate a value for the possible efficiency of the system it can be treated as a Carnot cycle. This is a large assumption since the duck operates under non-reversible conditions and the vapour pressure cycle and the

Carnot cycle differ. The Carnot assumption will yield the maximum possible efficiency for operation between two given temperatures. The simplest way to measure the Carnot efficiency is to measure the temperatures of the hot and the cold reservoirs. In the case of the duck these are not easily accessible but, with water evaporating from the head and the body maintained near room temperature, approximate values of working temperatures can be derived from a wet and dry bulb hygrometer. These will vary with the humidity and so will the efficiency of the duck. On a typical day in the south of England the temperatures were $T_{wet} = 14^{\circ}$ C , $T_{dry} = 19^{\circ}$ C

$$\therefore \text{ Carnot efficiency } \eta = \frac{T_{hot} - T_{cold}}{T_{hot}} \approx \frac{T_{dry} - T_{wet}}{T_{dry}}$$

$$= \frac{292 - 287}{292} = .02$$

This is the maximum efficiency which could possibly be achieved and it is small. The true efficiency could easily be an order of magnitude smaller. Of course, if energy is free, efficiency is not a prime consideration but even so the production of a useful engine based on 'duck' principles looks impossible. To extract say 1 kilowatt of power at least 50 kilowatts of heat would need to pass into the machine and that is not practicable. Theoretical considerations confirm the low power found experimentally in an earlier section.

Use of the Duck in Teaching

Details of how this model heat engine can be used to increase understanding of thermodynamics cannot be given here. Its major advantage is that it stimulates discussion. Primary school children are fascinated by it and will observe carefully until some of them describe what is happening and, in general terms, why it tips over. Secondary school boys and girls will be able to decide why the liquid

rises up the central tube and what it is that drives the machine. At higher levels no heat engine's laboratory should be without a 'drinking duck'. The simplicity of this engine contrasts with the size and complexity of the usual steam and internal combustion engines in engineering laboratories and discussion of its working principles provides a useful test of students' understanding of the thermal cycles of the big engines. Even physics and chemistry laboratories in universities and polytechnics would benefit from the presence of a duck. The discussion of pv diagrams above can be extended to temperature-entropy curves and the chemists might ponder the connection between their statistical treatment of entropy and the reality of a genuine heat engine.

At almost any level a project investigation can be based on the duck. Some questions that might be asked are 'What difference will it make if a liquid other than water is used in the glass?' 'Can you drive it with a cooling spray?' 'With a heat source?' 'What is the connection between relative humidity and the rate of oscillation.' 'Could it ever be a useful solar engine?' 'What other factors influence its performance?' 'Can you design and build a more efficient vapour pressure engine?'. Questions such as these require an experimental approach and the results are likely to stimulate further proposals. Schoolchildren and students will suggest other things to do. Perhaps one day someone will invent an engine which does derive continuous power from the atmosphere or the sea without making use of an obvious heat sink. Will that refute the second law of thermodynamics?

FROM ENERGY DEVALUATION TO EXERGY

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1. Introduction

In school, energy is mostly introduced as a conserved quantity: pupils are taught that it can neither be created nor destroyed. Critical pupils and students feel that this contradicts their experience, according to which
- fuel tanks of cars and trucks become empty,
- their parents have to pay for electrical energy, and gas as each month goes by,
- the depletion of (conventional) energy resources has taken energy into the focus of social-political interest.

All this indicates that energy may be consumed.

In order to avoid a discrepancy between what the pupil perceives as reality and the scientific description of reality, it must be stressed that 'conservation' and 'consumption' of energy are not contradictory concepts. They express two complementary aspects of common sense experience. Although the 'consumption' aspect has been conceptualized in physics by entropy, exergy, etc., these quantities are normally not treated in school. This is at least partially a consequence of the way in which entropy is introduced into the conceptual scheme of physics (BORN 1921): in fact this offers little chance to perceive any relationship between entropy and the experiences of energy consumption and to realize the signification of entropy within physics. The notion of exergy seems to be nearly unknown to physics teachers.

In this paper we shall sketch an introduction procedure of entropy resp. of the closely related concept of exergy. First of all, the experiences of energy consumption are conceptualized by the notion of 'energy devaluation' or 'degradation', which already leads to a far-reaching qualitative understanding. It offers a realistic opportunity to discuss the above mentioned problems in undergraduate physic courses.

The qualitative concept of 'energy devaluation', finally, is specified by the quantity of 'exergy', which takes our intention underlying the experiences of devaluation better into account than entropy does.

2. Energy consumption is energy degradation

Our everyday life experiences are determined by the 'consumption' of things of common use:
- In a household, water is used up for washing, cleaning, flushing the toilette, cooking potatoes, etc.
- Energy is used up for heating a room, driving a car, lighting a lamp, etc.
- Even clothes, cars, houses, etc., become worn out.

These examples show that consumption may be conceived as a devaluation or degradation of systems, for quantitatively they are unchanged:
- Spoiled (waste) water is discharged into the sewer.
- Consumed energy is emitted to the surroundings.
- Worn out clothes are thrown into the garbage can, cars onto the scrap yard.

The devaluation is a consequence of the fact that processes run down spontaneously only in one direction, but do not reverse by themselves. Therefore, a system running through a spontaneous process suffers an irrevocable change in that it can no longer be used for its original purpose: in this sense it is devaluated.

> The unidirectional running down of natural processes involves the consumption or devaluation of the systems under consideration.

In the following we focus our attention on processes, for which the devaluation may be described as devaluation of energy.

First of all, this obviously is possible for processes which (nearly) do not change the system in question. A radiator, heating a room, a vacuumcleaner, cleaning a carpet, a running car stay unchanged.

In these cases, the devaluation is due to the energy consumption which consists in the transmission of the driving energy to the surroundings, representing an irreversible process, i.e. a process which spontaneously does not run backwards.

Other examples, like the cooling of a cup of tea, the rolling down of a stone from a hill, or the shining of a candle, emphasize the change of the corresponding system, which may be conceived as energy devaluation in that the system irrevocably transmits energy to the surroundings. Actually, the first-mentioned examples are of the same kind, if one persues the path of the energy back to the oil- or gas tank, or the coal supplies of the power plants.

> Energy devaluation may be conceived as a decrease of the energy of a system and a corresponding increase of the energy of the surroundings.

To conceptualize the irreversibility of processes, reflecting the experiences of energy consumption, resp. energy devaluation, one may start from the fact that these processes can be forced to run backwards removing the devaluation, resp. effecting a corresponding revaluation.

For example,the tea water may be reheated by means of an electric range; the stone may be brought back to the top of the hill by means of a cableway, and the candle may be replaced by a new one.

But the removal of the devaluation i.e. the revaluation caused by the reversal of the processes is far from being the only

thing happening in the world. Together with the reversal of the one process, another process has to run down in its natural direction, thus being accompanied by a corresponding devaluation of energy.

> The reversal of a spontaneous process α, and therewith the removal of the corresponding energy degradation $\Delta V(\alpha)$, may be forced by another spontaneous process β. In short: An energy revaluation may be driven by an energy devaluation.

In accordance with the above described experience, that spontaneous processes (running down in their natural direction) are always accompanied by an energy degradation, one may consider the ability of a process to reverse another spontaneous process (thereby removing the energy degradation) as a measure of the energy degradation.

> That one of two processes is combined with a greater devaluation of energy, which is capable to drive the other one backward, thus removing the corresponding devaluation.

Therefore, the use of energy may be regarded as the activity of men to prevent spontaneous processes (e.g. the burning of oil, the flowing of electrical current) from simply running down without effecting anything else (e.g. the burning of oil in an open field, the operating of an immersion heater in a lake), but forcing them by means of appropriate devices to reverse other useful processes, so that - in case of need - they may run down again producing heat, movement, sound, light, etc. in various forms for human requirements.

The greater the energy revaluation due to the reverse process driven by the energy devaluation of another spontaneous process, the greater the yield of energy.

In the limiting case the revaluation caused by the reversal of the one equals the devaluation due to the other. Altogether there should be no devaluation. In reality, this case cannot be achieved, because it presupposes vanishing process velocities, i.e. the total standstill. In this sense, energy devaluation is the driving mechanism of every event.

Saving energy means, therefore, harnessing a process to revalue as much energy as possible under given conditions.

3. Measuring the energy degradation

3.1 Energy devaluation of (isothermal) dissipation

Experience shows that one of two given processes is always capable of reversing the other one. Therefore, the above mentioned endeavour to save energy by deriving the optimal profit from a given process may be used to measure the energy devaluation.

> The energy devaluation $\Delta V(\beta)$ associated with a process β is determined by the maximal energy revaluation which can be effected by β.

This measuring procedure presupposes the convention (already used implicitely above), that the reversal $-\alpha$ of a natural process α may be ascribed to a corresponding negative devaluation, i.e. a corresponding revaluation:

$$\Delta V(-\alpha) = -\Delta V(\alpha), \qquad (1)$$

and the value change $\Delta V(\alpha \oplus \beta)$ combined with the process $\alpha \oplus \beta$ composed of the partial processes α and β is the sum of the partial value changes $\Delta V(\alpha)$ and $\Delta V(\beta)$:

$$\Delta V(\alpha \oplus \beta) = \Delta V(\alpha) + \Delta V(\beta). \qquad (1a)$$

The quantitative comparison of the value changes due to different processes may be illustrated by means of two processes of the sort: "Falling down (and staying down) of a weight", which only differ in their mass. By means of a lever the falling of the one weight is used to move up the other, i.e. by means of one process, the other is driven backwards. A more detailed analysis (BACKHAUS et al. 1981) shows that, in the limiting case, it is possible to move up five weights of the mass $m_\beta = 0.4$ kg by means of two weights of the mass $m_\alpha = 1$ kg and vice versa. The twofold running down of the process α reverses the process β five times and vice versa:

$$\Delta V(2\alpha) + \Delta V(-5\beta) = 0 \Leftrightarrow \Delta V(\alpha) = \frac{5}{2}\,\Delta V(\beta). \qquad (2)$$

The devaluation mechanism of these processes is the dissipation of mechanical energy (emission of energy to the surroundings). The dissipated energy is proportional to the mass of the weights. Therefore, the above result that the energy devaluation is proportional to the mass of the weights may be generalized.

> The devaluation ΔV due to isothermal dissipation is proportional to the energy decrease ΔE_m of the mechanical system: $\Delta V \sim \Delta E_m$.

The dissipation within a (thermal) reservoir of low temperature (process α) may be conceived as composed of a dissipation process within a reservoir of a higher temperature (process β) and a heat conduction process (γ) between the two reservoirs. As the heat conduction is a natural process

associated with energy devaluation, the process α, considered as composed of β and γ, effects a greater energy devaluation than β.

$$\left.\begin{array}{l}\Delta V(\alpha) = \Delta V(\beta \oplus \gamma) = \Delta V(\beta) + \Delta V(\gamma) \\ \Delta V(\gamma) > 0\end{array}\right\} \Rightarrow \Delta V(\alpha) > \Delta V(\beta). \qquad (3)$$

> The energy devaluation due to isothermal dissipation is the greater, the lower the temperature is at which it occurs:
> $\Delta V = c(\theta)\ \Delta E_m$,
> where $c(\theta)$ is a monotone decreasing function of the temperature θ measured in any empirical scale.

Investigations of ideal gases show that $c(\theta) = c/T$, where c is a constant and T the absolute temperature (BACKHAUS et al. 1981, pp. 153 ff and 290).

3.2 Energy devaluation as value change of systems

Thus far, energy devaluation has been discussed for processes in which energy is conserved: The energy decrease in one of the systems involved leads to an energy increase (of the same amount) in the other one. Very often the attention is directed only to the energy change of one of the systems i.e. to one part of the natural process. For example, in the case of the weight moving up or down (see above) one is not so much interested in the energy change of the surroundings as in the energy decrease or increase of the weights. This suggests that one conceives the devaluation of a natural process as composed of the energy devaluation due to the system emitting energy and the (numerically smaller) revaluation of the system receiving this energy. According to this view, as a result of a dissipation process of the above mentioned kind the value

of the mechanical system would decrease and the value of the thermal system would increase such that the total value change amounts to:

$$\underset{<0}{\Delta V_{Diss}} = \underset{<0}{\Delta V_m} + \underset{>0.}{\Delta V_{th}} \qquad (4)$$

Here the sign of the value change is fixed in such a way that revaluations are counted positively and devaluations negatively.

Such a decomposition of a measurable quantity is always somewhat arbitrary (compare e.g. the fixing of the zero point of the energy or of the electrical potential). But this may be restricted by special conditions: requiring additivity for the value changes of systems (i.e. the value change of a composed system equals the sum of the value changes of the single systems), the change of state of mechanical systems may be written

$$\Delta V_m = c_m \cdot \Delta E_m, \qquad (5)$$

because the energy exchange between mechanical systems is reversible. c_m is the same constant for all mechanical systems.

From this the value changes ΔV_{th} of thermal systems may be derived:

$$\Delta V_{th} = \Delta V_{Diss} - \Delta V_m = \frac{c}{T}\Delta E_m - c_m \Delta E_m = \left(c_m - \frac{c}{T}\right)\Delta E_{th}. \qquad (6)$$

This expression is, as we have shown, the result of a stepwise precision of those experiences, which may be gained in connection with energy consumption.

The constants, still open, may be fixed according to expedience.

In the following we shall fix the constants such that known quantities will result and examine to what extend they are

compatible with the above-described conception of energy devaluation, resp. value changes, due to energy exchanges.

3.3 Entropy

Putting $c_m = 0$ and $c = 1$ (eq. (6)) one gets

$$\Delta V_m = 0 \quad \text{and} \quad \Delta V_{th} = - \Delta E_{th}/T. \tag{7}$$

In this case ΔV_{th} equals (with the exception of the sign) the entropy change ΔS of the system:

$$\Delta V_{th} \equiv - \Delta S.$$

This choice of constants leads to a well known physical quantity. But it does not perfectly reproduce the above developed conception of value changes due to energy exchanges, because

- the energy change of a mechanical system does not lead to a value change of the system, whereas
- the energy increase of a thermal system would suffer a devaluation.

3.4 Exergy

The following choice of constants: $c_m = 1$, $c = T_U$ (where T_U is the absolute temperature of an appropriate reservoir (generally the surroundings), yields:

$$\Delta V_m = \Delta E_m (>0 \text{ for } \Delta E_m > 0) \tag{8}$$

$$\Delta V_{th} = (1 - T_U/T) \cdot \Delta E_{th} \begin{cases} >0 \text{ for } T>T_U, \\ <0 \text{ for } T<T_U \end{cases} \text{if } \Delta E_{th} > 0 \tag{9}$$

$$\Delta V_{Diss} = \frac{T_U}{T} \Delta E_m (<0 \text{ for } \Delta E_m < 0) \tag{10}$$

At first sight, the result (9) seems to contradict our intention because it admits a devaluation due to the energy intake of a thermal system. But carefully considered, it generalizes the concept of energy devaluation, resp. value change, of systems to temperatures $T<T_U$, which until now has been discussed only for $T > T_U$. In the case of such systems (with $T < T_U$) the absorption of energy from the surroundings taking place spontaneously, thus is accompanied by a devaluation, whereas the emission of thermal energy (forced by other spontaneous processes) from the "cold" system to the "warm" surroundings leads to an revaluation.

As will be shown later on, the quantity introduced here to describe the value change due to the energy change of a system, corresponds to the quantity of exergy change, which is used especially in technical thermodynamics (e.g. BAEHR 1981, p. 137).

Exergy change and value change are therefore considered as synonymous quantities.

Summarizing the qualities of the value change resp. exergy change established thus far we get the following statements:

- Natural processes are combined with a decrease of the total exergy of the systems involved. This 'exergy principle' is the quantitative counterpart to the above mentioned 'principle of energy degradation'.
- The exergy change of mechanical systems is equal to their energy change.
- The exergy of a thermal system increases with increasing energy if it is warmer than the surroundings. The exact statement is given by eq. (9).
- The energy change of the surroundings does not cause any exergy change.
- The exergy has the same dimension as the energy. Its unit can be therefore 1 Joule. The unit is operationally defined by a process α_o = 'dissipation of 1 Joule mechanical energy at the temperature T_U of the surroundings'.
- The exergy change combined with a process amounts to x Joule, if by this process the process α_o can be reversed

x times; i.e. if an energy of x Joules may be transferred from the surroundings to a mechanical system.

3.5 Exergy as value of the energy

For stationary processes, which do not change the state of a system (see the above-mentioned examples), it turns out to be better to assign the value change to the exchanged energies. This intention may be realized by the concept of exergy: As the value, resp. exergy change, associated with an energy change ΔE manifests itself in the intake or output of work W, resp. heat Q, by a mechanical, resp. thermal system, a value, resp. an exergy, may be assigned to the exchanged work, resp. heat. Thus, assigning the exergy

$$\varepsilon_W = \Delta V_m = \Delta E_m$$

to the work W and the exergy

$$\varepsilon_Q = \Delta V_{th} = (1-T_U/T)\Delta E_{th}$$

to the heat Q, the everyday life experience that (mechanical or electrical) work is the most valuable and heat a less valuable energy form is formulated quantitatively. As can be realized qualitatively, the exergy of the heat ε_Q depends on the temperature of the system, which emits or absorbs the heat. If heat is emitted by a system at the temperature T_1, and absorbed by another system, at the temperature $T_2<T_1$, it has suffered a devaluation, which corresponds to the difference of the exergy of the heat emitted and the exergy of the heat absorbed. The transfer of work to a thermal system has to be conceived as a transformation of work into heat within a surface layer of the thermal system and an absorption of this heat accompanied by an exergy change corresponding to the temperature of the thermal system.

4. Energy transformation

To which extent different energy forms may be transformed into each other is governed by the principle of energy degradation or exergy decrease. Because of the so-called exergy factor of the heat $(1-T_U/T)$, the maximal amount of energy which can be obtained as a result of a given energy transformation may be different from the initial amount of energy. For instance, heat may even in principle not be transformed totally (by a cyclic process) into work, whilst work may yield an even greater amount of heat. The energy principle is satisfied by the fact that the surroundings are involved, the energy changes of which do not lead to exergy changes.

In the following the greatest possible extent of energy transformations is calculated by means of the exergy principle for the transformations: heat → work (heat engine) and work → heat (heat pump).

4.1 Heat engine (HE)

A heat reservoir of temperature T is supposed to emit the heat Q into a HE. The HE transmits Q partly as work W to a mechanical system and partly as heat Q' at the temperature T' to the surroundings. (The mean change of state of the HE is zero.) The exergy $\varepsilon_{Q'}$ and ε_W represented by the heat Q' and the work W cannot, with regard to the exergy principle, be greater than the exergy ε_Q of the supplied heat Q:

$$\varepsilon_W + \varepsilon_{Q'} \leq \varepsilon_Q \Leftrightarrow W + Q'(1-T_U/T') \leq Q(1-T_U/T).$$

Because of $Q' = Q - W$

$$W \leq Q(1-T'/T) < Q \quad \text{at} \quad T > T'.$$

Thus, even in principle, less work is gained than heat has been supplied. If one succeeds in transferring Q' at the temperature $T' = T_U$ to the surroundings, the possible work output W can be increased, because in this case even the exergy

ε_Q, of the waste heat Q' may be exploited, which will be zero at $T' = T_U$. Because of

$$W \leq Q(1-T_U/T) = \varepsilon_Q \quad ,$$

the exergy ε_Q represents the maximum work W which may be obtained from the heat Q under ideal conditions. In this way the exergy is commonly introduced (e.g. BAEHR 1981, p. 136).

4.2 Heat pump (HP)

A HP is supposed to take work W from a mechanical system, heat Q' from a thermal system (e.g. ground water) at the temperature T' and to give both in form of heat Q to a thermal system at the temperature $T > T'$. Q is limited by the principle that the exergy ε_Q cannot exceed the sum of the exergies ε_W and $\varepsilon_{Q'}$:

$$\varepsilon_Q \leq \varepsilon_W + \varepsilon_{Q'} \Leftrightarrow Q(1-T_U/T) \leq W + Q'(1-T_U/T').$$

Because of $Q' = Q - W$

$$Q \leq W/(1-T'/T) > W \quad \text{at} \quad T > T'.$$

According to this the amount of heat emitted at the higher temperature T may be greater than the amount of the supplied work W. In realistic cases HP's yield two to three times more heat Q to the thermal system (e.g. an appartment) than the work W that has been supplied.

Finally, it should be mentioned that the devaluation, resp. exergy decrease, which drives the energy revaluation, resp. exergy increase, by means of a HP, may not only be caused by the dissipation of work but also by an appropriate heat conduction process. This process is limited only by the condition that there will be no net production of exergy. Such a transformation may be achieved by means of an absorption HP,

which is driven e.g. by burning gas. Operating such a HP as refrigerator, we get the paradoxical possibility to cool something by means of heat.

5. Summary

- The exergy represents a quantity by which a value may be attributed, in a straight forward way (i.e. in accordance with a value concept drawn from common sense considerations), to a given energy transformation.
- The exergy reflects the experience gained from energy problems that each real process is accompanied by a devaluation of energy. This experience is the common sense equivalence of the second law of thermodynamics (entropy principle), which within the scope of the exergy concept, expresses the impossibility of an (overall) exergy increase.
- The emphasis of the temperature of the surroundings as zero point of the exergy within the exergy concept corresponds very well to the common sense experience of energetic processes.
- The exergy permits a direct conceptualization of the conspicuous parts of everyday energetic phenomena, without being obliged to take those unconspicuous parts into account which would be important with respect to the energy principle.
- The value, resp. exergy, concept permits one to explain the energy loss , but also the energy gain , which are principally present at most of the energy transformations. By pointing especially to those energy gains, one may be able to bring the students to become aware of a source of energy wastes which, energetically regarded, must be overlooked. This could be taken into account, on the basis of the exergy concept, by replacing the ordinary efficiency determining the relation between the energetic yield and the energetic expenditure by the exergetic efficiency which relates the actual yield to the maximally possible yield, thus incorporating the values of the energy forms involved (SCHLICHTING et al. 1982).

Compared with this the entropy principle, an important notion within physics, does not correspond very well to the value concept experienced in everyday life. This could be one of the reasons for the minor rôle the entropy concept plays in school physics. Finally, it should be stressed that the exergy concept is not restricted to highschool physics. On the contrary, this concept being based directly on everyday life experience of the pupils allows, already in undergraduate physics, the understanding of qualitative characteristics of energy devaluation, a foundation to a later introduction of the quantity of exergy.

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ENTROPY, THE REINCARNATION OF THE LATE CALORIC

ENTROPIE, DAS WIEDERERSTANDENE CALORIUM - DIE GESCHICHTE DER WÄRMELEHRE EINMAL ANDERS BETRACHTET!

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1. Einleitung

Die Entropie gilt als eine der wichtigsten, aber auch unanschaulichsten und abstraktesten Größen der Physik. Ist diese Unanschaulichkeit unvermeidlich, sozusagen der Preis für die umfassende Anwendbarkeit dieser Größe? Eine nähere Analyse zeigt, daß die Entropie nicht an sich unanschaulich ist, sondern daß sie diese Eigenschaft historischen Zufälligkeiten verdankt. Es ist nicht schwerer, sich ein anschauliches Bild von der Entropie zu machen als eins von der Energie, ja in mancher Hinsicht ist es sogar leichter. Der springende Punkt dabei ist, daß eine einfache Anschauung der Entropie aufs engste mit dem Gebrauch des Wortes "Wärme" zusammenhängt. Die mit diesem Wort verknüpften Assoziationen sind weitgehend durch unsere Umgangssprache bedingt, und diese entscheiden darüber, was wir als anschaulich empfinden und was nicht.

Für den heutigen Physiker ist Wärme eine "Energieform". Nach der gängigen Lehre scheint das eine definitive Einsicht in die Natur zu sein, so daß eine Diskussion darüber gewöhnlich Skepsis, wenn nicht gar Mißtrauen auslöst. Mit der Gewissheit über die Natur der Wärme verbindet sich auch das verbreitete (Vor-)Urteil, daß alle Vorstellungen falsch sind, die man sich vor der Etablierung der Energie als allgemein-physikalischer Größe, also vor den 40iger Jahren des letzten Jahrhunderts, von der Wärme gemacht hat. Wer verläßt nicht Schule oder Universität mit der Überzeugung, daß die alte Vorstellung, Wärme sei eine Art Substanz, die gewöhnlich unter ihrem historisch letzten Namen "Caloricum" bekannt ist, falsch und ein typischer Irrtum der Vergangenheit sei?

Die Energieform Wärme hat aber einige recht tückische Eigenschaften. Wer seine Thermodynamik gut gelernt hat, weiß, daß die Energie zwar in

Form von Wärme in einen Körper hineinströmen oder aus ihm hinausströmen kann, daß es aber falsch und daher verboten ist, sich vorzustellen, die Energie sei auch als Wärme im Körper enthalten. Sobald die Wärme im Körper angekommen ist, hört sie auf, Wärme zu sein; sie ist dann bloß noch Energie, die sich lediglich in der Erhöhung des Wertes der (inneren) Energie des Körpers äußert.

Wie lassen sich diese Forderungen mit den einfachen Bildern in Einklang bringen, die die Umgangssprache in jedem Menschen erzeugt, nämlich daß "Häuser deshalb isoliert werden, damit die in ihnen befindliche Wärme nicht so leicht hinausfließt", oder daß Wärmespeicher deshalb so heißen, weil "Wärme in ihnen gespeichert wird". Schließlich versteht jeder auf Anhieb, was der Satz "Reibung erzeugt Wärme" besagt. Aber alle diese Sätze sind wissenschaftlich falsch, wenn Wärme eine Energieform ist. Sie müssen schon deshalb falsch sein, weil sie auch bereits im 18. Jahrhundert so lauteten wie sie heute noch lauten und damals für jedermann ebenso verständlich waren wie heute.

Alle diese Schwierigkeiten (und noch eine Reihe weiterer) verschwinden, d.h. alle obigen Sätze bleiben auch wissenschaftlich richtig, wenn der Physiker das Wort "Wärme" nicht in dem ihm gewohnten Sinn verwenden würde, sondern als Synonym für Entropie. Damit würde gleichzeitig auch die Entropie mit einer altvertrauten Anschauung belegt. Tatsächlich ist die Clausiussche Entropie nichts anderes als das alte Caloricum, das nur deshalb so schwer wiederzuerkennen ist, weil es bei seiner Rückkehr in die Reihe der physikalischen Größen unter der Maske großer Abstrakheit auftrat und damit als Neuling erschien.

So betrachtet ist die Entropie sogar älter als die Energie und vermutlich schon deshalb nicht schwerer zu verstehen. Ein Blick in die Geschichte der Wärmelehre soll das belegen.

2. Die Menge und die Stärke der Wärme

Obwohl die Beschäftigung mit dem Phänomen der Wärme ebenso alt ist wie die Beschäftigung mit dem Bewegungsproblem, hat sich die Wärmelehre deutlich anders entwickelt als die Mechanik. Einmal vollzog sie sich viel langsamer als die Mechanik, zum anderen stammen die wesentlichen

Beiträge zu ihr weniger von Mathematikern oder mathematischen Physikern als von Chemikern, Ärzten und Ingenieuren.

Die historisch erste herausragende Figur in den Bemühungen zur begrifflichen Aufklärung der Phänomene der Wärme ist der schottische Chemiker und Arzt Joseph Black (1728-1799). Black erkannte (und etwa gleichzeitig mit ihm auch Johann Heinrich Lambert (1728-1777)), daß es zur Erfassung der Wärme zweier verschiedener, voneinander unabhängiger Begriffe bedarf, nämlich der Menge der Wärme und der Stärke der Wärme. In seinen "Lectures on the Elements of Chemistry" (Edinburgh 1803) findet sich für den ersten dieser beiden Begriffe folgende Erklärung:[1,2]

> "Wenn wir z.B. ein Pfund Wasser in einem Gefäß haben und zwei Pfund in einem anderen, und wenn diese beiden Mengen gleich warm sind, wie das Thermometer anzeigt, so ist es klar, daß die zwei Pfund die doppelte Menge der Wärme haben, die in einem Pfund enthalten ist."

Diese Erklärung ist unzweideutig und klar, die Wärme ist nach Black eine mengenartige Größe: Sie ist in den Körpern enthalten, und sie kann in die Körper hereinströmen und aus ihnen hinausströmen.

Die zweite Größe, die Stärke der Wärme, ist das, was als Temperatur bereits bekannt war. Sie stellt nach Black eine Art "Triebkraft" dar oder einen "Antrieb", mit dem die Wärme einen Körper zu verlassen trachtet. Sie ist eine Art "Spannung", unter der die Wärme in dem Körper steht. Werden zwei Körper in Berührung (heute sagen wir in "thermischen Kontakt") gebracht, so strömt die Wärme aus dem Körper, in dem ihre Stärke größer, d.h. die Temperatur höher ist, über in den Körper, in dem ihre Stärke geringer, also die Temperatur niedriger ist. Der Vorgang des Überströmens ist dann beendet, wenn die Wärme in beiden Körpern dieselbe Stärke hat, wenn also beide Körper dieselbe Temperatur haben. Black nennt diesen Zustand thermisches Gleichgewicht.

In der Symbolik der heutigen Zeit laufen die Blackschen Begriffsbildungen auf die Behauptung hinaus, daß es folgende Größen gibt:

S = Menge der Wärme, im folgenden kurz Wärme genannt. S ist in Körpern, allgemein in physikalischen Systemen enthalten und kann

als lokalisierbare Substanz vorgestellt werden.

I_S = Wärmestrom oder S-Strom. I_S wird positiv gezählt, wenn der Strom aus einem Körper hinausfließt.

T = Temperatur, sie mißt den "Antrieb" von S oder die "Spannung", unter der S in einem physikalischen System steht. Das Temperaturmaß kann beliebig gewählt werden, allerdings mit zwei Einschränkungen: 1. von zwei sich berührenden Körpern hat der den größeren Wert von T, aus dem der Wärmestrom hinausfließt; 2. fließt bei Berührung kein S-Strom, so haben beide Körper denselben Wert von T, sie stehen dann im thermischen Gleichgewicht.

Es sei angemerkt, daß eine Substanzvorstellung der Wärme auch von anderen Forschern des 17. und 18. Jahrhunderts entwickelt worden ist. Zunächst trug diese Wärmesubstanz den Namen "Phlogiston" (Becker, Stahl, Scheele), später, nämlich Ende des 18. Jahrhunderts, den Namen "calorique" oder "Caloricum" (Lavoisier, Berthollet, de Fourcroy und de Morveau). Bei dieser Vorstellung ging es allderdings nicht so sehr um die begriffliche Fassung der Wärme als um die Frage ihres Zusammenhangs mit den chemischen Verbrennungsvorgängen.

3. Die Wärmekapazität

Mit der Vorstellung, daß die Wärme wie eine Substanz in einem Körper enthalten ist und herein- und hinausströmen kann, verbindet sich, wie die Bemerkungen zum Überströmen von Wärme zwischen zwei Körpern und dem sich schließlich einstellenden thermischen Gleichgewicht zeigen, ganz unmittelbar die Vorstellung, daß bei Zunahme der in einem Körper enthaltenen Wärme S die Temperatur T des Körpers ansteigt, zumindest nicht fällt. In mathematischer Ausdrucksweise bedeutet das, daß

$$\Gamma = \frac{\partial S}{\partial T} \geq 0 \quad . \tag{1}$$

Die Größe Γ nannte Black die Wärmekapazität des Körpers. Daß sie, wie (1) aussagt, nicht negativ ist, hat einen einfachen Grund. Brächte man nämlich einen Körper mit negativer Wärmekapazität in thermischen

Kontakt mit einem Körper, dessen Wärmekapazität positiv ist, so würde, falls die Temperatur des zweiten größer ist als die des ersten, beim Überströmen der Wärme vom zweiten zum ersten die Temperatur beider Körper sinken. Nähme man als zweiten Körper außerdem noch einen, dessen Wärmekapazität kleiner ist als der Absolutwert der (negativen) Wärmekapazität des ersten, so würde bei thermischem Kontakt die Temperatur beider Körper sinken, und zwar unter ständiger Zunahme der Temperaturdifferenz: Die Körper würden sich infolge ihres thermischen Kontaktes "von selbst" abkühlen, und ein thermisches Gleichgewicht käme nie zustande.

Die Betrachtung zeigt, daß im Rahmen der Blackschen Beschreibung der Wärmephänomene die Wärmekapazität Γ eine brauchbare Größe ist und daß ihre Nichtnegativität wichtig ist, wenn alle möglichen Körper in die Betrachtung einbezogen werden, wenn man also eine allgemeingültige Theorie im Auge hat. Heute nennen wir die Bedingung der Nichtnegativität von Γ eine thermodynamische Stabilitätsbedingung.

Historisch bemerkenswert war die Bereitschaft, mit der der Begriff der Wärmekapazität aufgenommen wurde. Vermutlich hatte das mit der Hoffnung zu tun, mit seiner Hilfe das "richtige" Temperaturmaß zu finden. Man empfand es als unbefriedigend, daß, von der Anordnung abgesehen, die Definition der Temperatur eine ganze Reihe von Freiheiten enthielt: 1. Wahl der Thermometersubstanz, 2. Wahl der Meßgröße X (Druck, Volumen, relative Volumänderung), 3. Festlegung der Funktion T=f(X). Die Hoffnung bestand darin, daß bei Benutzung des "richtigen" Temperaturmaßes, die Wärmekapazitäten der Körper oder vielmehr ihre spezifischen Wärmekapazitäten $\gamma = \Gamma / m$ (m = Masse des Körpers) für den Stoff, aus dem der Körper besteht, temperaturunabhängig und damit charakteristische Konstanten würden. Diese Hoffnungen schwanden indessen mehr und mehr, beginnend mit den Untersuchungen von Lavoisier und Laplace in den 80iger Jahren des 18. Jahrhunderts über die Temperaturabhängigkeit der spezifischen Wärmekapazität, und endgültig mit einer Arbeit von Doulong und Petit im Jahre 1817. Inzwischen aber hatte sich der Begriff der Wärmekapazität so eingebürgert, daß er in den Untersuchungen nach wie vor eine entscheidende, ja oft genug überbetonte Rolle spielte.

4. Die latente Wärme

Schreibt man Gl. (1) in der Form

$$\Delta S = \Gamma \Delta T \quad , \tag{2}$$

so drängt sich leicht die Vorstellung auf, daß die in einem Körper enthaltene Wärme S und die Temperatur T des Körpers immer durch eine Beziehung der Form (2) verknüpft sein könnten. Daß das jedoch nicht zutrifft, ja daß die Vorgänge des Schmelzens und des Verdampfens - also das, was wir heute Phasenübergänge nennen - dafür ein direkter Beleg sind, war für Black ein besonders handgreiflicher Beweis für die Sinnvollheit und Existenz der Größe S. In einer Reihe von genial einfachen Experimenten und Beobachtungen zeigte er, daß das Schmelzen von Eis und das Verdampfen von Wasser bei konstant gehaltenem Druck, d.h. unter Bedingungen, die jedem vertraut sind, ohne Temperaturänderung verlaufen, daß diese Vorgänge aber trotzdem die Zuführung leicht meßbarer Mengen von Wärme erfordern. Die zum Schmelzen einer Menge Wassers der Masse Δm erforderliche Wärmemenge ΔS ist gegeben durch

$$\Delta S = \Lambda \Delta m \qquad (\Delta T = 0) \quad . \tag{3}$$

Die Größe Λ nannte Black die latente Wärme der Phasenumwandlung, und so wird sie heute noch genannt. Gl. (3) läßt sich auch schreiben

$$\Lambda = \frac{\partial S(T,m)}{\partial m} \quad . \tag{4}$$

Hier wird zum ersten Mal der Sinn der bereits in (1) verwendeten partiellen Differentiationssymbole deutlich: Es ist damit zu rechnen, ja es ist sicher, daß die in einem Körper enthaltene Wärme S mit anderen physikalischen Größen des Körpers zusammenhängt, mindestens - wie aus Blacks Vorgehen zu entnehmen ist - mit m und T, in Wirklichkeit aber, wie wir sehen werden, noch mit weiteren, insbesondere mit Volumen und Druck. Diese Abhängigkeit der Wärme S von mehreren Größen erwies sich historisch als eine ernste Klippe, die nicht nur für das Schicksal des Blackschen Begriffssystems, sondern für die ganze Entwicklung der Wärmelehre im folgenden Jahrhundert mitentscheidend war.

5. Adiabatische Vorgänge

Wenn es um die Frage geht, von welchen physikalischen Größen eines Körpers die in dem Körper enthaltene Wärme S abhängt, so bietet sich als naheliegende Antwort die folgende an: Man halte S konstant und untersuche, welche anderen Größen sich unter dieser Bedingung noch in ihren Werten ändern lassen und wie diese Änderungen untereinander zusammenhängen. Diese Antwort suggeriert geradezu eine experimentelle Untersuchung, nämlich den betrachteten Körper mit einer wärmeundurchlässigen (= adiabatischen) Hülle zu umgeben und die Veränderungen zu studieren, die unter dieser Umhüllung noch möglich sind.

Was waren die Gründe, daß diese Art Experimente lange Zeit gar nicht gemacht wurden, 1807 dann von Gay-Lussac zwar gemacht, aber in ihrer physikalischen Aussage nicht voll erkannt wurden und erst 1823 durch Poisson und 1824 durch Carnot ihre Aufklärung erfuhren? Eine mögliche Antwort ist zwar die, daß bei Beschränkung auf flüssige und feste Körper derartige Experimente nicht naheliegen, da bei solchen Systemen eine adiabatische Isolation das Volumen praktisch festlegt und den Druck vom Volumen entkoppelt. Aber das kann nicht der entscheidende Grund gewesen sein, denn man hatte sich seit langem mit Gasen beschäftigt, und seit den 80iger Jahren des 18. Jahrhunderts war bekannt, daß Gase, die in die freie Luft expandieren, sich abkühlen. Daß bei dem umgekehrten Vorgang, d.h. bei adiabatischer Kompression sich Luft z.B. erhitzt, ja sogar sehr stark erhitzen kann, entdeckte kein Physiker, Chemiker oder Arzt. Ein Arbeiter der französischen Gewehrfabrik zu Etienne en Forez machte 1803 eine praktische Anwendung dieses Effektes in dem von ihm erfundenen pneumatischen Feuerzeug. Dann erst begannen die Naturwissenschaftler sich dafür zu interessieren. Der wichtigste Grund dafür, daß die adiabatischen Vorgänge so gut wie übersehen wurden, ist vermutlich der, daß von allen Blackschen Begriffen die "abgeleiteten", insbesondere die Wärmekapazität, mehr akzeptiert wurden als die grundlegende Größe S, die Wärme. So wurde die Logik geradezu herumgedreht.

Vom Standpunkt des Blackschen Begriffssystems beweist das pneumatische Feuerzeug, daß die in einem Gas enthaltene Wärme S mit der Temperatur

T, dem Druck p und der durch die Masse m gemessenen Menge des Gases zusammenhängt, daß also S=S(T,p,m). Hält man nämlich die Menge des Gases, also m, und überdies S fest, so folgt aus S(T,p,m)=const., daß, wie beobachtet, T eine Funktion von p ist.

6. Die Erzeugbarkeit der Wärme S

War es offenbar schon schwer genug, die Tatsache zu akzeptieren, daß die in einem Gas enthaltene Wärme S nicht nur von der Temperatur T und der Masse m des Gases abhängt, sondern auch vom Druck p, so offenbarten die 1807 veröffentlichten Experimente Gay-Lussacs eine zweite Tatsache, die noch viel schwerer zu akzeptieren gewesen wäre, wenn sie überhaupt erkannt worden wäre, nämlich daß die in einem System enthaltene Wärme S nicht nur durch den Einstrom, sondern auch durch Erzeugung von Wärme im System selbst vermehrt werden kann.

Die Erfahrung, um die es dabei geht, läßt sich an adiabatischen Expansionsvorgängen im Prinzip einfach demonstrieren. Ein Gas sei in einen mit einem beweglichen Kolben verschlossenen Zylinder eingeschlossen. Die Wände des Zylinders und der Kolben seien aus wärmeundurchlässigem Material gefertigt, so daß die nachfolgenden Prozesse unter adiabatischer Isolation ablaufen (Abb. 1).

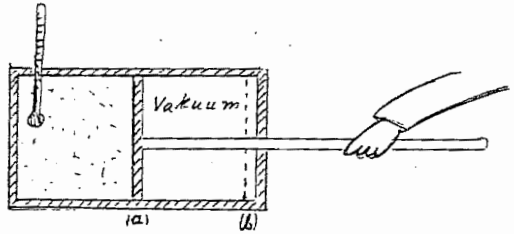

Abb. 1

Man betrachtet nun folgenden Vorgang: Der Kolben wird von einer Ausgangsposition (a) in eine Endposition (b) gebracht, danach wieder von (b) nach (a) zurück. An einem Thermomether kann die Temperatur des Gases bei den unterschiedlichen Positionen des Kolbens abgelesen werden. Das Experiment liefert folgende Resultate:

- Wird der Kolben hinreichend langsam von (a) nach (b) bewegt, so kühlt sich das Gas von der Anfangstemperatur T_a auf eine Temperatur $T_b(\min) < T_a$ ab. Wird der Kolben dann ebenfalls langsam wieder von (b) nach (a) gedrückt, so nimmt die Temperatur des Gases wieder den Anfangswert T_a an.

- Wird der Kolben schnell von (a) nach (b) bewegt, so kühlt sich das Gas weniger ab, und zwar umso weniger, je schneller die Bewegung des Kolbens erfolgt. Die sich einstellende Endtemperatur T_b ist direkt ein Maß dafür, wie schnell der Kolben von (a) nach (b) bewegt wurde. Bei "unendlich schneller" Bewegung (die man dadurch realisiert, daß man den Kolben bei (a) plötzlich zerbricht oder durchlöchert) ergibt sich eine höchste Endtemperatur $T_b(\max) \leq T_a$. Gay-Lussac schloß übrigens aus seinen Messungen, daß bei einem idealen Gas $T_b(\max)=T_a$ ist. Die möglichen Endtemperaturen T_b füllen also ein ganzes Intervall $[T_b(\min), T_b(\max)]$ aus.

Wird nun nach einer beliebigen dieser "schnellen" Expansionen der Kolben wieder nach (a) zurückgebracht (zweckmäßigerweise langsam damit nichts unvorherzusehendes passiert), so hat das Gas stets eine Temperatur $T'_a > T_a$. Man kann das Gas dadurch wieder auf seine Anfangstemperatur T_a bringen, daß man ihm eine bestimmte, durch $T'_a - T_a$ festgelegte Wärmemenge $\Delta S'$ entzieht. Da während des ganzen Vorgangs des Expandierens und nachfolgenden Komprimierens das Gas in wärmeundurchlässige Wände eingeschlossen war, ihm also Wärme weder zugeführt noch entzogen werden konnte, bleibt nur der Schluß: Die Wärmemenge $\Delta S'$, die dem Gas entzogen werden muß, um es wieder in seinen Anfangszustand zu bringen, wurde erzeugt.

Ein weiterer Schluß, der aus dem geschilderten Experiment zu ziehen ist, ist der, daß das Einschließen eines Körpers in eine wärmeundurchlässige Hülle keineswegs garantiert, daß die im Körper enthaltene Wärme S ihren Wert beibehält, also S=const. ist. Letzteres ist, wie es scheint, nur der Fall, wenn außerdem die unter adiabatischer Isolation noch möglichen Vorgänge langsam genug ablaufen. Tatsächlich äußert sich hier der 2. Hauptsatz: Bei allen unter adiabatischer Isolation eines Systems noch möglichen Vorgängen kann die in dem System enthaltene Wärme S zwar zunehmen, aber niemals abnehmen; eine Abnahme von S ist nur dadurch möglich, daß die S-undurchlässige Hülle geöffnet wird und Wärme wegströmt. Jede einmal irgendwo erzeugte Wärmemenge ΔS kann daher nur dadurch wieder beseitigt werden, daß sie

aus dem betrachteten System in ein anderes, meist "Umgebung" genannt, abgeschoben wird. Es ist aber unmöglich, eine einmal erzeugte Wärme wieder zu vernichten, in physikalischer Terminologie: Die Erzeugung von Wärme ist irreversibel.

Wir sagten schon, daß diese Schlußfolgerungen seinerzeit nicht gezogen worden sind, obwohl sie hätten gezogen werden können. Es ist aber durchaus anzunehmen, daß wenn sie gezogen worden wären, vermutlich dasselbe passiert wäre wie 30 Jahre später, nämlich daß Blacks Wärme S, die inzwischen nur noch unter dem Namen "calorique" lief, zu einem mit den Tatsachen "in Widerspruch stehenden, also falschen Begriff" erklärt worden wäre. Zu stark war damals das auch heute immer noch vorhandene alte philosophische Vorurteil wirksam, daß alles Substanzartige notwendig einem generellen Erhaltungssatz genügen müsse. Die Vorstellung, daß Dinge und damit Substanz entstehen und verschwinden können, gibt es zwar in der literarischen Phantasie des Menschen, wie z.B. im Märchen, aber in der wissenschaftlichen Phantasie finden solch unsolide Vorstellungen nicht so leicht ihren Platz.

7. Carnot: Wärme und Arbeit

Sadi Carnot (1796-1832) brachte 1824 in seiner Abhandlung "Réflexions sur la puissance du feu et sur les machines propre à développer cette puissance" eine neue Fragestellung in die Beschäftigung mit der Wärme, nämlich die nach dem Zusammenhang zwischen Wärme und Arbeit.[3] Ausgelöst wurde diese Frage durch die große wirtschaftliche Bedeutung, die die englischen Dampfmaschinen zu dieser Zeit bereits errungen hatten. Aus dem praktischen Problem der Verbesserung dieser Maschinen, nämlich dieselbe Arbeit - meist durch das Hochpumpen einer bestimmten Menge Wassers aus einer bestimmten Schachttiefe gemessen - mit dem Verbrennen von möglichst wenig Kohle zu erreichen, machte Carnot eine wissenschaftlich generelle Frage: Gibt es eine obere Grenze für die von einer Wärmekraftmaschine gelieferte Arbeit, und wodurch ist diese Grenze bestimmt?

Carnots Abhandlung enthält tatsächlich die Grundlagen zur ganzen heutigen Thermodynamik. Es ist deshalb unmöglich, sie hier in ihren Details zu umreißen. Daß die von Carnot entwickelten Ideen die

Grundlagen einer Theorie dieses Umfangs enthielten, mag Carnot selbst zwar geahnt haben, durchschaut hat er es kaum - und noch weniger haben das jene Forscher getan, die die Thermodynamik dann auf andere, allerdings viel kompliziertere und undurchsichtigere Weise aufgebaut haben, nämlich Mayer, Joule, Thomson und Clausius.

Von den Resultaten der Carnotschen Überlegungen interessieren in unserem Zusammenhang vor allem die folgenden beiden:

- Die bei Black noch in ihrem Maß freie Temperatur wird unabhängig von der Art der Systeme, an denen und mit denen sie gemessen wird, festgelegt, sie wird zur absoluten Temperatur T.

- Neben die Wärme S - die Carnot "calorique" nennt, und die heute Entropie heißt - tritt eine von S unabhängige zweite mengenartige Größe E auf, die Carnot in Anlehnung an den Sprachgebrauch der Mechanik Arbeit nennt und die heute den Namen Energie trägt.

Es sei noch einmal ausdrücklich betont, daß in Carnots Theorie Wärme S und Energie E zwei verschiedene mengenartige Größen sind. Die Energie E kann ebenso als eine in einem Körper enthaltene "Substanz" vorgestellt werden wie die Wärme S, und wie letztere in einen Körper herein- oder aus ihm hinausströmen kann, so kann auch die Energie herein- und hinausströmen. Neben dem Wärmestrom I_S gibt es also auch einen Energiestrom I_E.

Eine zentrale Aussage der Theorie ist nun, daß I_S, I_E und die absolute Temperatur T durch folgende generelle Regel miteinander verbunden sind: Fließt ein Wärmestrom I_S aus einem Körper der absoluten Temperatur T hinaus, so wird dieser Wärmestrom stets von einem Energiestrom I_E begleitet, der den Betrag hat

$$I_E = TI_S \quad . \tag{5}$$

Mit F. Herrmann sagen wir auch, der Energiestrom (5) wird von dem Wärmestrom I_S "getragen". Mit dieser Aussage folgt sofort: Fließt ein Wärmestrom I_S aus einem Körper der (festen) Temperatur T_2 heraus, so muß mit ihm auch ein Energiestrom vom Betrag $T_2 I_S$ aus dem Körper herausfließen. Läßt man dann denselben Wärmestrom I_S in einen anderen

Körper mit der (ebenfalls festen) Temperatur $T_1 < T_2$ strömen, so fließt mit ihm auch wieder ein Energiestrom vom Betrag $T_1 I_S$ in diesen Körper. Damit bleibt ein Energiestrom ΔI_E übrig, dessen Betrag gegeben ist durch

$$\Delta I_E = T_2 I_S - T_1 I_S = (T_2 - T_1) I_S = \frac{T_2 - T_1}{T_2} (T_2 I_S) \quad .$$

Nun bezeichnet man bekanntlich den Quotienten $\Delta I_E / T_2 I_S$ als den (maximalen) Wirkungsgrad η einer Maschine, die den Übergang von Wärme von einem Körper höherer Temperatur T_2 auf einen Körper tieferer Temperatur T_1 zur Lieferung des Energiestroms ΔI_E ausnutzt: Es ist $\eta = (T_2 - T_1)/T_2$.

8. Die Entwicklung der Wärmelehre nach 1840

Mit der Entdeckung der Energieerhaltung durch R. Mayer, J.P. Joule und andere wurde die Entwicklung der Wärmelehre, wie sie sich seit einem Jahrhundert vollzogen hatte, abgebrochen und auf eine andere Weise fortgesetzt. Man hatte eine Größe entdeckt, die, wie es aussah, einem allgemeinen Erhaltungssatz genügte und die es nun in der Theorie unterzubringen galt. Wie selbstverständlich fiel dabei der Blick auf die Wärme S, Carnots "calorique". Man sah nicht, daß die Theorie noch eine zweite Größe anbot, nämlich E. Da inzwischen aber längst bemerkt worden war, daß Wärme erzeugt werden kann, S also keinen allgemeinen Erhaltungssatz befolgt, sah man keinen anderen Ausweg als den, die ganze Theorie, vor allem ihre grundlegenden Begriffe für "falsch" zu erklären.

Von hier ab ist die Geschichte der Wärmelehre jedem Physiker bekannt. Die neu entdeckte Energie E wurde zur zentralen Größe im Neuaufbau der Wärmelehre. Dem Wort "Wärme" gab man eine neue Bedeutung, nämlich die, eine "Form der Energie" darzustellen. Auch die "Arbeit" bekam eine ähnliche Bedeutung, sie wurde eine von der Wärme verschiedene Form der Energie. Die Energie war nicht nur eine allgemeine, an jedem physikalischen System auftretende Größe, sie hatte nach Ansicht ihrer Entdecker eine zweite Eigenschaft, die sie von anderen Größen unterschied: Sie konnte sich in verschiedene Formen "verwandeln". F. Herrmann hat in seinem Vortrag diese Merkwürdigkeit näher behandelt, so

daß es sich erübrigt, hier darauf einzugehen.

Als ein wissenschaftliches Ereignis besonderer Bedeutung wurde dann aber die recht abstrakte und mühevolle Konstruktion einer neuen Größe durch Clausius empfunden, die er Entropie nannte. Clausius konstruierte sie mit Hilfe der Energieform Wärme, der von W. Thomson (Lord Kelvin) nach dem Vorbild Carnots definierten absoluten Temperatur und dem Begriff des reversiblen Prozesses. Die merkwürdigste Eigenschaft dieser neuen Größe schien die zu sein, daß ihr Wert bei irreversiblen Prozessen zunimmt. Das diese Größe auch mengenartig ist, ließ ihre Konstruktion nicht erkennen, und so ist es kein Wunder, daß ihre Mengenartigkeit auch nicht klar erkannt wurde. Das Merkwürdigste aber ist, daß man nicht erkannte, ja bis heute nicht erkennt (oder erkennen will), daß diese Entropie nichts anderes ist als die alte Blacksche Wärme S.

9. Die Rolle der Hauptsätze in der Thermodynamik

Um den Inhalt einer Aussage recht deutlich zu Bewußtsein zu bringen, ist es didaktisch oft vorteilhaft, sie im Kontrast zu ihrer Negierung oder einer ihr widersprechenden Alternativaussage zu sehen. Betrachtet man so die Aussage des 1. Hauptsatzes, ergibt sich eine merkwürdige Situation: Da es nach ihm in der Welt überhaupt nur Prozesse gibt, bei denen die Energie erhalten bleibt, man also gar keine anderen kennt, ist der Satz entweder eine Tautologie, oder er stellt die wirklichen Prozesse in Gegensatz zu möglichen Prozessen, die es aber gar nicht gibt. Der Satz bekommt überhaupt nur einen Sinn vor dem Hintergrund einer Beschreibung der Welt, d.h. einer Theorie, in der es mehr Möglichkeiten von Prozessen gibt, als wir wirklich beobachten. Die Thermodynamik muß also Aussagen enthalten, die unabhängig sind davon, ob der 1. Hauptsatz gilt oder nicht gilt. Entsprechendes muß für den 2. Hauptsatz zutreffen.

Welche Aussagen der Thermodynamik sind nun unabhängig davon, ob die beiden Hauptsätze gelten, d.h. unabhängig davon, ob die Energie erhalten und die Entropie unvernichtbar ist? Die Antwort ist ebenso einfach wie überraschend: Alle sich in mathematischen Gleichungen ausdrückenden Relationen zwischen den physikalischen Größen sind

unabhängig davon, ob es für die Entropie ein Vernichtsverbot und für die Energie ein Erzeugungs- und Vernichtsverbot gibt oder nicht.[4,5] Um es noch pointierter zu sagen: Alle Formeln, die physikalische Größen miteinander verbinden, d.h. aber alle in den Lehrbüchern der Physik vorkommenden Formeln sind unabhängig von den Hauptsätzen. Wenn also eines Tages entdeckt würde, daß die Energie doch nicht immer einem Erhaltungssatz genügt, oder es auch Fälle gibt, in denen Entropie vernichtet werden kann, so würden diese Formeln nicht falsch.

Welche Funktion haben aber dann die Hauptsätze innerhalb der Theorie? Sie stellen Aussagen darüber dar, wie sich die Änderungen der Energie E und der Entropie S eines Systems realisieren lassen. So läßt sich die Energie E eines Systems nur dadurch ändern, daß ein zweites System zur Verfügung steht, das die Änderungsbeträge ΔE der Energie liefert oder aufnimmt. Bei einer Änderung ΔS der Entropie S des Systems ist dagegen nicht unbedingt ein zweites System erforderlich, wenn die Änderung eine Zunahme, also $\Delta S > 0$ ist, während ein zweites System erforderlich ist, wenn $\Delta S < 0$ ist. Ob aber eine Zunahme seiner Entropie S dadurch zustande kommt, daß der Betrag ΔS von einem zweiten System in das betrachtete System überströmt, oder dadurch, daß ΔS innerhalb des Systems selbst erzeugt wird, oder ob schließlich beides passiert, "merkt" das Systems gar nicht, es "spürt" nur die Änderung ΔS seiner Entropie S, nicht aber wie sie zustandekommt. Infolgedessen können auch die Beziehungen, die die Entropie S des Systems mit anderen physikalischen Größen des Systems verbinden, nicht davon abhängen, ob die Entropie erzeugt worden ist, ja ob sie überhaupt erzeugbar ist oder nicht.

Damit hat aber auch die Eigenschaft der Entropie, mengenartig zu sein, also in einem Körper enthalten zu sein und in ihn herein- oder aus ihm hinausströmen zu können, logisch nichts mit ihrer im 2. Hauptsatz festgestellten Eigenschaft der Unvernichtbarkeit zu tun. Deshalb läßt sich die für ein einfaches, anschauliches Bild der Entropie so wichtige Eigenschaft der Mengenartigkeit, nämlich ihre Lokalisierung und ihres Strömens, nicht aus ihrer Eigenschaft des Nicht-Abnehmen-Könnens herleiten.

10. Didaktische Schlußfolgerungen

Unsere Betrachtungen zeigen, daß die Entropie dadurch zu einer anschaulichen Größe wird, daß sie mengenartig, also eine Art Substanz ist. Deshalb ist es auch sinnvoll, sie nach einem Vorschlag von G. Job[6] Wärme zu nennen, denn dieses Wort impliziert infolge seiner gewohnten sprachlichen Verwendung die Assoziation des Mengenartigen. Auf diese Weise bekommt man auch ohne physikalische Vorkenntnisse eine Anschauung von der Entropie und ein Gefühl dafür, wie man mit ihr zur Beschreibung von Naturvorgängen umzugehen hat. Dieses Bild ist nicht nur qualitativ brauchbar, es bleibt bis in die quantitativen Einzelheiten hinein tragfähig und erlaubt so ohne Schwierigkeit die Behandlung nicht nur physikalischer, sondern auch chemischer und biologischer Vorgänge.

Mit der Anschauung der Mengenartigkeit einer Größe verbindet sich nun, wie die Erfahrung zeigt, nahezu zwangsläufig die Vorstellung, daß diese Größe auch erhalten sein müsse. Die Masse und die elektrische Ladung bilden hierfür bekannte Beispiele. Ein anderes liefert die Geschichte des Blackschen Wärmebegriffs. Sobald klar war, daß die Wärme keinen allgemeinen Erhaltungssatz befolgt, stellten sich Zweifel an der Sinnvollheit des Begriffs überhaupt ein und führte schließlich dazu, ihn für "falsch" zu erklären, ohne daß sich nennenswerter Widerspruch dagegen erhob.

Der Lehrende kann also damit rechnen, daß sich mit der Vorstellung der Mengenartigkeit der Entropie automatisch die Erwartung ihrer Erhaltung verbindet. Die Behandlung reversibler Vorgänge - das sind ja gerade die, bei denen die Entropie erhalten bleibt - schließt sich damit wie selbstverständlich an. Einer gesonderten Mühe bedarf es schließlich noch klar zu machen, daß ein "halber Erhaltungssatz" für die Entropie, nämlich daß sie zwar nicht abnehmen, wohl aber zunehmen kann, die Möglichkeit bietet, Möglichkeit bietet, auch die Phänomene der Irreversibilität mit diesem Begriff zu fassen.

Würde man dagegen versuchen, umgekehrt vorzugehen, also die Irreversibilität als primäre Eigenschaft zu betrachten und sie demgemäß an den Anfang stellen, so geriete man notwendig in Schwierigkeiten, wenn es darum geht, die Mengenartigkeit der Entropie

einzusehen. Es ist ja, wie wir gezeigt haben, logisch gar nicht möglich, sie aus der Eigenschaft der Entropie, nie abnehmen zu können, herzuleiten. Andererseits ist die Mengenartigkeit der Entropie aber unverzichtbar, wenn es darum geht, mit dieser Größe auch praktisch zu arbeiten.

Die letzte Bemerkung ist von Bedeutung vor allem im Hinblick auf die verbreiteten Bemühungen, die Entropie von Seiten ihrer wahrscheinlichkeitstheoretischen Eigenschaften her begreiflich zu machen. Es ist klar, daß dieses Vorgehen geradezu darauf hinausläuft, die Entropie von der Einseitigkeit ihrer Wertänderungen aus zu verstehen. Es steht außer Frage, daß Boltzmanns Idee, die zeitliche Gerichtetheit natürlicher Vorgänge mit dem einseitigen Verlauf von Zufallsprozessen in Zusammenhang zu bringen, zu den tiefgründigsten Gedanken darüber gehört, wie wir mit unseren physikalischen Begriffen die Natur beschreiben. Aber es ist ebenso klar, daß es sehr schwierig ist und viel intellektuelle Delikatesse dazu gehört, diese Idee zu vermitteln, ohne sie zu einer simplen Würfelei werden zu lassen. Man vergesse nicht, daß es Boltzmanns Ziel war, die Entropie im Rahmen der einst allmächtigen Mechanik zu verstehen (in dem er auch die Elektrodynamik zu verstehen suchte), genauer diese Größe in die Mechanik einzubauen. Das Mittel dazu sah er in der Wahrscheinlichkeit des zeitgerichteten Zufallsvorgangs, den er mit Hilfe des Begriffs der Stoßverteilung und der Hypothese der "molekularen Unordnung" in die Mechanik einzubauen versuchte. Diese Konstruktion nachzuvollziehen, ist indessen so mühevoll, daß sie höchstens dem Berufsphysiker zugemutet werden kann. Aber selbst wenn man diese Mühe auf sich zu nehmen bereit ist, hat man noch lange nicht die Mengenartigkeit der Entropie erfaßt, die ihrerseits nur mit weiteren Hypothesen zu gewinnen ist. Die Entropie auf dem Boden der Mechanik zu verstehen, ist in der Tat so schwierig, daß nur eine lange und ausgiebige Beschäftigung mit dem Gegenstand schließlich eine Vertrautheit schafft, die es erlaubt, mit dieser Größe auch zu arbeiten. Sieht man in der Entropie dagegen von Anfang an die mengenartige Größe, so ist sie selbst anschaulich und der Umgang, auch der quantitative Umgang mit ihr sehr einfach.

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"ENTROPY IS CONSIDERED TO BE ONE OF THE MOST IMPORTANT BUT LEAST UNDERSTANDABLE CONCEPTS OF PHYSICS."

G.Falk

"IS THE SECOND LAW TOO DIFFICULT A TOPIC FOR MOST OF THE STUDENTS? OR IS AN UNEASY FEELING AMONG TEACHERS AND MEMBERS OF SYLLABUS COMMITTEES CONCERNING THE CONCEPT OF ENTROPY RESPONSIBLE FOR THE MINOR ROLE THE SECOND LAW PLAYS IN PHYSICS INSTRUCTION?"

Reinders Duit

ENTROPY AS AN ENERGY CARRIER

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1. Introduction

It will be shown in this paper, that it is misleading to give the expressions $\vec{F}\vec{ds}$, TdS, μdn etc. names of their own such as work, heat etc. and to call each of them an "energy form". It is argued that the concept of energy form be dropped altogether and that energy transports be classified by means of a concept more appropriate to the energy's substance-like nature: energy carrier. It will be seen that with this concept the teaching of entropy is as easy as the teaching of, say, electric charge or amount of substance.

2. SUBSTANCE-LIKE QUANTITIES

There is a class of physical quantities whose characteristics are especially easy to visualize: Those extensive physical quantities to which a density and a current can be assigned. These include electric charge, momentum, angular momentum, entropy, amount of substance (number of particles) energy and others. Because of the fundamental role these quantities play throughout science, we give them a designation of their own: substance-like.

If a quantity is substance-like, it makes sense to say it is contained within a region of space. This means, it makes sense to ask about the amount of such a quantity within a region of space and to relate changes in this amount to the flow of this quantity to or from the considered region. Indeed it is appropriate to speak about the local conservation or non-conservation of a quantity only if this quantity is substance-like and if it obeys or violates a continuity equation. On the other hand, it is inappropriate to speak about the conservation or non-conservation of non-substance-like quantities such as, say, electric field, temperature or velocity. Some substance-like quantities are always conserved, for

example, electric charge, whereas other substance-like quantities are conserved only under special circumstances such as amount of substance (if no chemical reactions are taking place). Thus, 'substance-like' and 'conserved' are not identical concepts: 'substance-like' is more comprehensive.

3. ENERGY FORMS

The term 'energy form' is used together with a profusion of different names such as rest or mass energy, kinetic energy, thermal energy, gravitational energy, binding energy, radiant energy, elastic energy, potential energy, electrical energy, chemical energy, nuclear energy and so on. A careful student might rightly be confused in trying to figure out, say, whether the energy contained within a battery is in the form of electrical or chemical energy. It might seem that the concept of energy form has a rather ambiguous physical interpretation and, consequently, that the importance of the concept is more colloquial than scientific. The purpose of this section is to provide a rigorous definition of energy form.

Energy can be classified in two completely different ways[1,2]: Firstly by how energy changes or, what usually amounts to the same thing, how energy flows, and secondly by how energy is stored. In the first case, one arrives at concepts like: electrical energy, chemical energy, heat, work, etc. . In the second case, one refers to concepts like: internal energy, electric field energy, kinetic energy, potential energy and so on. Unfortunately, many books speak of energy forms in both cases.

In this paper we deal only with the first classification, i.e. the classification of energy changes or energy currents.

Experience shows that energy always flows simultaneously with the flow of at least one other substance-like quantity. This statement expresses a law of nature. It can be written as

$$I_E = \varphi I_Q + \mu I_n + \vec{v} \vec{I}_p + T I_S + \dots \quad . \tag{1}$$

Here, I_E, I_Q, I_n, I_p and I_S stand for an energy-, charge-, molar-, momentum-[3,4] and entropy-current, respectively, while φ, μ, $\vec{v}$ and T

represent the electric potential, chemical potential, velocity and absolute temperature. For example, energy flows (as specified by the Poynting vector field) to a toaster simultaneously with the flow of electric charge through the wires leading to the device; energy flows together with amount of substance (fuel + oxygen) into a car engine; energy flows together with momentum through a rope pulling a wagon and energy flows together with entropy through the wall of a house. In such cases, one speaks of the transfer or exchange of energy in one or another "form" according to the physical quantity which flows simultaneously with the energy, Fig. 1.

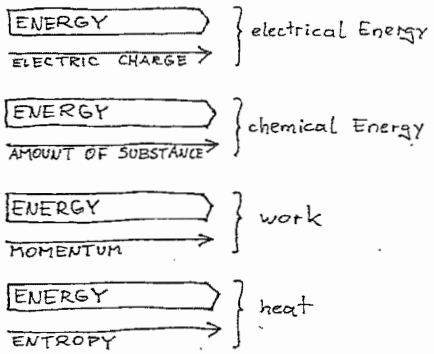

Fig. 1

In the above examples, one speaks of electrical energy, chemical energy, work and heat, respectively. Incidentally, the same technique can be used to classify energy forms in terms of the physical quantities which change along with the energy change of a system. Such a classification is expressed mathematically by the Gibbs Fundamental Form well-known from thermodynamics [1].

In contrast to classifying stored energy, which is not always possible, energy currents can always be classified according to equation (1). Thus, the classification of energy currents is more general than the partitioning of stored energy into various terms.

4. ON THE INAPPROPRIATENESS OF THE CONCEPT OF ENERGY FORM [5]

If we accept the above classification of energy currents, what then is wrong with the general concept of energy form? The best way to answer this question is to consider the answer to yet another, for example: "What would be wrong with speaking about different forms of electric charge?" In other words, why don't we give different names to the electric charge, e.g. 'electronic charge', 'protonic charge' 'myonic charge', 'Cl-ionic charge' according to the charge carrier involved during a transfer of charge? For example, why don't we say that ionic charge is "converted" into electronic charge (or vice versa) at the electrodes of a battery or that protonic charge is converted into positronic charge in β^+-decay? Obviously, giving different names to the electric charge could lead to the mistaken impression that these designate different physical quantities when only one and the same physical quantity is involved in each case: electric charge. If the substance-like nature of energy is taken just as seriously as the substance-like nature of electric charge, then speaking about different forms of energy is just as misleading as speaking about different forms of charge would be. It is not the energy being transported through the electromagnetic field, a fuel line or a house wall which has different characteristics but, rather, the other substance-like quantity which flows simultaneously with the energy in each case. Consequently, energy is not actually transformed or converted within a so-called "energy transformer" or "energy converter". Rather, it is correct to say that the other substance-like quantity which flows along with the energy is exchanged within such a device. For example, energy is brought into a power plant together with coal and oxygen or, scientifically speaking, together with the amount of substance (the quantity measured in moles) of coal and of oxygen and energy always flows out of the power plant simultaneously with electric charge. Energy flows simultaneously with the flow of electric charge into a motor winding up a rope and energy flows out again through the rope along with momentum, Fig. 2.

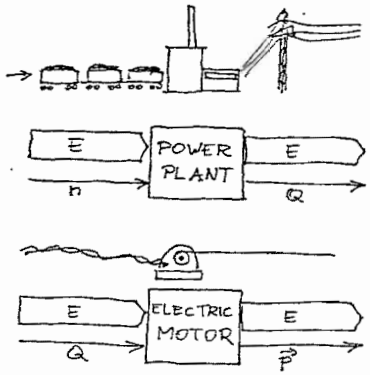

Fig. 2

Let us consider a parable in order to further illustrate the inapropriateness of the term energy form. Consider some commodity, say potatoes, which changes its carrier during transport. Potatoes often have a long way to go from the field to the household: They are carried by a tractor trailer from the field to a pick-up truck which takes them to a station where they are loaded onto a train, transported to another city, reloaded onto a delivery truck and then brought to a supermarket where they get into the basket of the customer. Nevertheless, no one would think to label potatoes differently during each stretch of their trip, for example, 'tractor potatoes', 'pick-up potatoes', 'train-potatoes', 'delivery potatoes' and 'marketing potatoes'. No one would speak of different 'potatoe forms' just because the potatoes have different carriers . No one would say that potatoes are converted when they are unloaded from the truck and loaded onto the train. We can go even further with this comparison. For example, no one would think to give potatoes an entirely different name, say, 'truck retarder' or 'biostarch', during some particular part of their trip. Nevertheless, this is just what is done in the case of energy when one speaks of 'heat' or 'work'.

There is yet another problem when speaking about energy forms. For explicitness consider the 'energy form' heat: Every physicist learns that it is correct to say heat is flowing into a body but it is incorrect to say that then this heat is contained within the body. This does not mean that the heat which is flowing into a body is destroyed just when it is entering the body, the situation is more paradox: it means that, physically, it makes no sense to speak about heat which is contained

somewhere. In the same way it is true that chemical energy enters a combustion cell but then no chemical energy is contained in it. The physical situations cited here are extremely simple, but their description is intricate and scholastic. (By the way, we believe that, although they don't confess to it, the profound, conviction of many physicists is that heat is indeed contained within a cup of hot coffee. This would mean that by heat they understand entropy S, and not TdS.)

If all reasonable arguments are against using different names for various energy transports, why then are these concepts so firmly established in physics? The explanation is simple. When the concept of energy was developed in the second-half of the last century and when its conservation was discovered, no intrinsic property of energy was known. Energy manifested itself differently in different physical systems and an energy current manifested itself differently in different processes. Energy and energy flows were recognized by other variables, but not always the same ones. In this situation it seemed reasonable to say that energy exists in different forms. Only since the advent of the theory of relativity do we know that energy is something of its own, something with its own properties, independent of the energy "form": energy is a source of the gravitational field.

5. ENERGY CARRIERS

If it is agreed that the term 'energy form' is misleading and inadequate to distinguish between different energy transports what other term could be used to better replace it? The answer becomes obvious by asking the analogous question about electric charge (or about potatoes). The answer is: energy carrier [6,7,8]. We say that the substance-like physical quantity which flows while energy is flowing, 'carries' the energy. It is an 'energy carrier'. And we say the carrier is 'loaded' with energy. We give two examples.

When a wagon is being pulled with a rope, instead of "the force acting on the wagon is doing work" we say "energy is flowing through the rope; the energy is being carried by momentum". Here the traditional wording is still reminiscent of the old action-at-a-distance picture.

Instead of saying "heat is being exchanged or transmitted" we say "energy is flowing; this energy is being carried by entropy", or if Job's suggestion[9] is admitted "energy is being carried by heat".

The picture of energy carriers is especially useful to describe devices which are traditionally called 'energy transformers' or 'converters'. Traditionally speaking, energy flows into an energy transformer in one form and out in another. Unfortunately, this way of speaking suggests that one physical quantity is transformed into another within such a device. Actually, however, the energy simply changes its carrier within the device. In other words, energy is transferred from one carrier to another within the device. Accordingly, the name energy transceiver is more appropriate to the actual function of such a device.

Our everyday natural and technological environment is full of examples of energy transceivers. For example, energy is transferred from the carrier 'electric charge' to the carrier 'entropy' within an electric oven and energy is transferred from the carrier 'amount of substance' to the carrier 'electric charge' within a power plant.

It is easy to graphically represent the energy transport from one device or region of space to another with the help of an energy flow diagram, Fig. 3 shows the flow diagram of a thermal power plant.

Fig. 3

An energy carrier can be "loaded" with more or less energy in the same sense that a carrier of commodities, say a pick-up truck, can be loaded with more or less of a commodity. For example, a 2 Ampere electric current can carry a greater or lesser energy current, say 1 kW or 10 W, depending upon the value of the potential. Accordingly, the electric potential is a measure of how much energy the energy carrier 'electric charge' (or "electricity") is loaded with. The electric potential is an energy load factor. Many other familiar intensive variables are also energy load factors. For example, the absolute temperature T is a measure of how much energy an entropy current is loaded with and the chemical potential μ is a measure of how much energy a molar current is loaded with. It is easy to

see the importance of many intensive physical variables if their role as energy load factors is emphasized.

Of course, there are limits as to how literally the expression 'energy carrier' should be understood. The word 'carry' implies here only a temporal relationship between the flow of energy and the flow of an energy carrier. It is not meant to imply that energy and its carrier necessarily occupy the same position in space or even flow with the same velocity. The example of the energy carrier 'electric charge' amply illustrates this point. The expression 'energy carrier' is a didactic tool which can be used to considerable advantage if not applied too naively.

We would like to mention that the structure we have shown to hold for energy transports has a correspondence in information transmission. An experiment is under way with 150 children where the concepts of information carriers, transceivers etc. are used.

6. ON THE TEACHING OF ENTROPY AND OTHER ENERGY CARRIERS

We have tried to convince the reader that it is not advantageous to assign different names to various energy transports. If this is accepted the word heat is free for another use.

G. Falk shows in his paper, that, if entropy S would be called heat, much would be done for the understanding of entropy.

These two conclusions fit well together. Hence, we propose the following agreement or definition:

Heat (= Entropy) is an energy carrier.

This is the verbal expression of the equation

$$I_E = TI_S .$$

With this decision the teaching of heat (= entropy) becomes just as difficult or easy as the teaching of say electric charge Q. We are convinced it becomes even easier: We have a natural feeling for the heat

content of a body via its temperature, whereas our feeling for electricity is very crude.

We will not display all the details of our proposal for the teaching of entropy. We will limit our considerations to one aspect, which may be the most important one.

The pupil or student has to be convinced that every transport is characterized by two substance-like quantities. This insight is often neglected in teaching energy - perhaps many teachers themselves are not aware of it. The problem does not only arise in teaching today, it played an important role in the history of the energy concept: Several times physicists tried to describe transport or exchange processes by one single substance-like quantity. We will give two examples.

The famous dispute between the Cartesians and Leibnizians was essentially about the question whether momentum or energy is the fundamental substance-like quantity of mechanics. Later it was recognized, that both quantities play important roles.

Some decades later the same scenario was repeated on the scientific stage, with different actors: First Carnot invented what we now call entropy, then Joule and Mayer invented thermal energy and it was thought that Carnot had been wrong. Finally Clausius showed that two substance-like quantities are necessary for the description of thermal processes.

To convince the pupils that two quantities are involved in a process several strategies can be applied.

1) The argument is topological. We will explain it with an example which is familiar to every teacher. Consider a simple electric circuit with a dynamo and a light bulb. What a beginner and a non-physicist notices first - in contrast to the prejudice of many physics teachers - is the flow of energy. He knows that something comes out of the light bulb and, in order that this happen, he has to turn the dynamo. Hence, something is going into the dynamo, through the connection between the dynamo and the light bulb and out of the light bulb. This is the experience of the first substance-like quantity: of energy. Then the teacher draws the pupil's attention to the fact that two wires are necessary, and that you can prevent the working of the light bulb by cutting any wire at any position. The electric connection behaves like the closed water circuit of a central heating system. This is a strong argument, that something is flowing within the wire. But this flowing substance is flowing around, it goes another way than the energy - it must be something else than energy, we call it electricity.

We used this argument by teaching electric charge and angular momentum to 11 to 12 year old children .

The same reasoning can be applied for showing that, for the description of thermal processes a second substance-like quantity is necessary besides energy. This was done with 17 year old pupils in the following way[10]. A thermal power plant is discussed. First the energy flow through the plant is studied. But then it is stated that a second output is necessary: The condensor. With a Stirling motor we show that if this output is blocked the engine stops working. We conclude that something is coming out here which cannot go out elsewhere and which is not energy. We call it entropy.

2) There is a second strategy to follow. We begin the teaching of energy transport with examples where it is obvious that, besides an energy current, there is a "carrier current" and we state the rule "For every energy transfer we need a carrier". By presenting many examples, the student gradually becomes convinced of the validity of this rule. If, then, a new process with a yet un-known energy carrier is considered, a carrier which might be invisible, the student will be more inclined to expect that there is an invisible energy carrier, than that there is none at all. We will give an example: in a class of 11 year old children we had introduced several energy carriers, among them electricity and angular momentum. At this time the concept of heat as an energy carrier was not yet known to the pupils. One day we began discussing the fuel stove and we asked the pupils to name the carriers for the incoming and for the outgoing energy. They told us: The incoming energy is carried by the fuel, the outgoing is carried by heat. They had invented the concept of entropy.

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ENTROPY AS AN INTUITIVE VARIABLE FOR MACROSCOPIC SYSTEM

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1. Introduction.

It is a known research result[1,2,3] that the mental representation of students of various phenomena often differ from the scientific ones also after specific courses on the subject. One possible explanation is searched in the relation between common sense knowledge and scientific knowledge[4] which, if not well clarified may act as a "critical barrier"[5] for the understanding of science. I do not know of specific research concerned with the concept of entropy but it is well known that heat and temperature are often confused[6]. Then it seems quite natural to expect that the analytical definition of S in terms of heat and temperature will present problems of understanding. On the other hand the definition of S in terms of order-disorder, related to the statistical description of a macroscopic system, may bring other problems on the ground: one may concern the understanding of the particulate model of matter with respect to its continuous appearance[7] and another may be related to the common sense meaning of order and disorder. In fact the word "entropy" until now does not seem to have acquired the same status in everyday language than that of the words "order" and "disorder".

In the following I will outline an introduction to entropy starting from the definition of thermodynamic system from the macroscopic point of view (par. 1), and analysis of the possible descriptions in terms of state and process (par. 2) which show the intuitive necessity of a state variable which describes the internal coordination of a macroscopic system (par.3).

Finally I will present (par. 4) some points for discussion.

1 - Thermodynamic system: definition.

In order to define a thermodynamic system one may initiate with a linguistic analysis of the words "system" and "thermodynamic": such an analysis will recall to the mind elements of common sense knowledge which are implicitly presupposed.

From an italian dictionary definition of system we may find that "a system is a plurality of material elements coordinated among them in such a way as to constitute an organic complex which obeys to give rules" or "an ensemble of parts put together according to some criterion". "Thermodynamic" on the other hand, as a whole word has meaning only as a section or chapter of physics and is otherwise non commonly used. The hearing of it may on the other hand suggest a tentative understanding in terms of the two words which are its components: thermo-dynamic. "Thermo" recalls immediately thermometer, thermos, temperature ....; "dynamic" of course has to do with movement, force or energy.

Putting together the pieces of this very rough linguistic analysis we can try a definition of thermodynamic system as:

- a system that produces movement or energy from temperature; and reciprocally
- a system in which movement or energy produce thermal effects.

Of course these definitions are still common sense definitions in some sense and do not permit given a particular real object or system to answer to the question "may this object be considered as a thermodynamic system?". Also a traditional course in general physics does not enable to answer to the question. At the University of Rome we have in fact posed to a small group of physics teachers and all the students in a third year course (general classical physics is taught in the first two years) the question shown in fig. 1 obtaining all sorts of answers (see fig. 2). The problem of course is connected with the way in which thermodynamic is taught at the University of Rome, but probably

Which objects, in the following list, are "thermodynamic systems" ?
Explain, for each object, the reason of your choice.
Add four examples of thermodynamic systems chosen among objects of common use.

- battery
- magnet
- yogurth
- piece of wax
- cat
- tree
- spring
- bacterial colony
- refrigerator
- piece of ice
- pot with boiling water
- container with helium at 10 atms
- gasoline tank
- thermos with warm milk
- the moon

Figure 1. Question posed for the definition of thermodynamic systems to students of physics at the University of Rome.

- All objects are thermodynamic systems only for 10% of the students.
- All objects characterized by P,V,T are thermodynamic systems for 20% of the students.
- Only the objects that exchange Q or E are thermodynamic systems for 19% of the students.
- 16% of the students make choices with explanation that exclude a part of the objects (for instance excluding the mechanical ones, or the electromagnetic ones, or the biological ones "because they are mechanical objects, etc.").
- 35% of the students make choices with no explicit explanation. The choices are such that the implicit explanation is difficult infer.

Figure 2. Distribution of the answers to the question

it is also related to the critical barrier between common sense and scientific definitions.

To answer to the question it is in fact necessary to understand first that a single object like a piece of wood may be considered a system in the sense of "a thing made up of different parts". If one takes into account the hypothesis of a particulate structure of matter than any macroscopic object may be thought of as constituted by a large but finite number of microscopic particles interacting among them on the basis of definite rules of interaction or confinement.

We have then two levels of the system concept:
any single object may be considered as a system in relation to its particulate structure, two or more objects may constitute a system when they are interacting.

Secondly, on the basis of the common sense definitions explicited by the linguistic analysis, to answer to the question of fig. 1 it is necessary to know if some or any macroscopic object may in some particular context or situation produce thermal effect or be transformed due to thermal causes.

For the second part we know by common sense knowledge or experience that everything is destroyed or changed by fire. This would be sufficient to conclude that all objects listed in table 1 are thermodynamic objects. The other part of the knowledge needed (is it true that any object in particular situations produces thermal effects?) is more subtle and also more interesting. The answer of course is yes, but it is not surprising that our students do not all know that electrical objects (resistor, battery), magnetic objects (magnets), biological objects (cat, tree, yogurth, bacterial colony), mechanical objects (moon, spring), technological objects (refrigerator, gasoline tank), materials (wav, ice, water, milk....) are also thermodynamic objects: no one ever directed their attention on thinking on the problem. The mechanical case is particularly interesting since

its teaching usually precedes that of thermodynamics but being directed to the formulation of conservation principles does not generally point out in a sufficiently explicit way the relation between the mechanical and thermodynamical descriptions[8]. Thermodynamics on the other hand is so much related to the perfect gas behaviour (so useful for introducing kinetic theory) and to the functioning of thermal engines that it is not surprising at all to find the distribution of answers of fig. 2.

2 - Thermodynamic system: descriptive variable.

Once defined a thermodynamic system, in order to proceed toward its scientific description we first touch upon the philosophical problem of the choice of the representation more apt to describe reality. Two alternatives have been obvious since ancient times[9]: a first philosophical conception asserts that reality consists of "things" and that every observed changement is secondary and depends from the way in which things interact one with another. From the other point of view, the world consists of "processes" and the things we see are just moments of equilibrium in what is essentially changement. The theory based on "things" is normally associated with the name of Democritus and the theory based on "processes" with the name of Eraclitus. The "thing" theory has been definitely successfull in the history of science also because a great number of phenomena around us has a time scale of changement very long compared with the time scale of our observation. Also in the development of thermodynamics a conception related to things (or states) has been finally successful notwithstanding the fact that in this case we are really interested in processes. Then the first problem is the definition of all possible equilibrium states of a thermodynamic system and processes are defined as what happens in the passage from one state to another. Classical thermodynamics is in fact a thermostatic[10] and true thermodynamics has not yet

been completely established.

However also in thermostatic the two aspects of state and process are continually mixing one with the other especially in the understanding of the theory. Discussing with a group of science teachers the best definition of a thermodynamic system on which all could agree was in fact related to the process conception: "A thermodynamic system is a system that can exchange 'things' (matter, energy and matter, heat, work) with other systems". This then caused difficulties in the understanding of the particular importance of defining, for the building up of thermostatic theory, the state variables. In fact a big step of abstraction is necessary to imagine from real transformations which happen in time, the ideal quasistatic transformations of the thermostatic theory related to a world without time.
In the didactical expositions however in general this steps is not even required and it is tacitly assumed that the state conception is the more intuitive one also in a case in which the real interest is in processes. (In fact also the word thermostatic is not yet used in manuals). On the other hand the known confusion made by students between heat and temperature is usually attributed to a difficulty in understanding the heat concept.
In the hypothesis that the reverse is true (heat, considered as a "process" concept, is a more intuitive concept than temperature) we have asked our students and a small group of secondary school-students to give the definition of both heat and temperature. In the great majority of answers heat is defined as a flow of energy (or something else) and temperature is then defined as what characterizes the state reached when the flow is finished or with the kinetic theory interpretation.

3 - Entropy and processes in the state conception.

Notwithstanding the importance of the description of real transformation and, as I said, the probable more intuitive understanding of the process concept, it is true than the theory of thermostatic has been successfull in describing real transformations and processes. It may seem surprising that a theory without time can describe the time evolution of a system.

This may be thought as due to the existence of materials with such thermal properties to permit an experimental connection between the process and state aspect. In examining the process definition of a thermodynamic system it is clear that the way to reduce processes to states is related to the experimental possibility of stopping the happening of a process. In order to do that we must be able to enclose a system in such a way that it cannot exchange matter or energy or both with the surroundings.

The existence of impermeable, semi-permeable, adiabatic materials and the knowledge of heat transfer processes then leads to the definition of "isolated, closed, adiabatic systems etc.". Let me stop a moment to reflect on the concept of isolated system, this cornerstone of thermostatic (the one in which energy is conserved and entropy, spontaneously grows toward a maximum) which from the process conception and from common sense may be considered a totally useless system as we cannot interact with it.

It should be made clear didactically that the isolated system concept is a theoretical construct required by our belief in the validity and usefulness of conservation laws. If a system does not exchange matter or energy or both, conservation of matter and energy are valid for such a system.

Reality is found then in good agreement with this theoretical definition as a general scheme of interaction like that of fig.3 may, in many cases of interest, be reduced to the simpler scheme

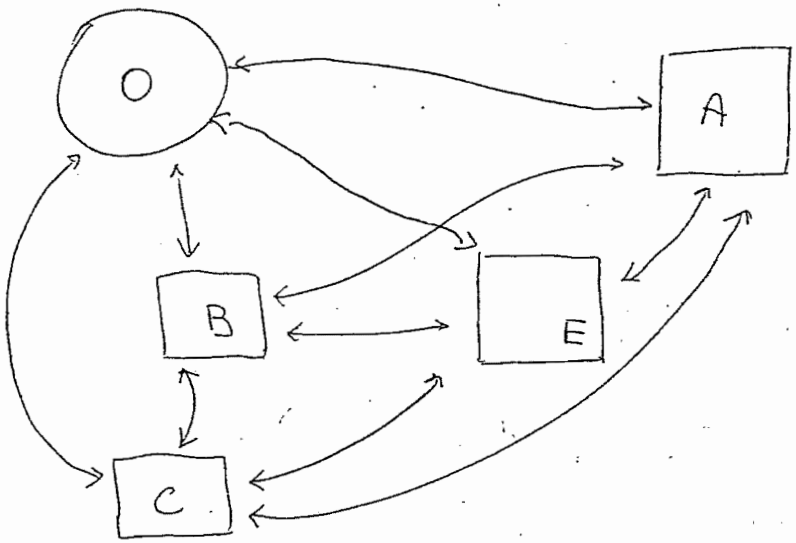

Figure 3. Schematization of four objects interacting among themselves and with the environment E.

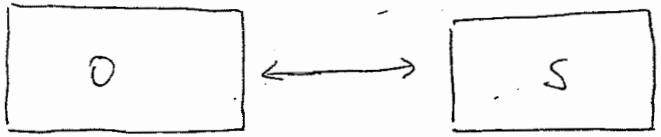

Figure 4. The simplest thermodynamic scheme in which one systems O interacts with only another system S, that may also indicate the environment.

of fig. 4*, in which the main interaction may be identified with a specific part of the environment and we can imagine to work with an isolated system made by the object of our interest and only a part of the environment. We can thus describe the properties of "open" systems through the properties of isolated systems.

As in an isolated system processes do not happen by definition, we are thus led to the state conception and to the definition of state variables.

Of course mass, energy and volume are three essential variables both of the parts that constitute the system (be that parts macro or microscopic) and of the system as a whole.

But a system is a system not only because it is made of parts but also because the parts are coordinated among them; thus we need an extra variable for the description of the system with respect to the description of its micro-component, a variable which describes the coordination. To this variable historically has been given the name of "entropy".

We are then left with the problem of relating this intuitively necessary variable with the known and measurable variables heat, temperature, volume.....

The relation

$$T\Delta S \geq Q$$

is then the explicit declaration of a reached agreement between the state conception and the process conception.

---

*Of course we are also interested in the general case, indeed complex systems behaviour is yet a research problem.

4 - Points for discussion.

In the didactical itinerary I tried to outsketch in the preceeding paragraphs there are many points for discussion.

This is precisely the reason why I presented it in this meeting.

I shall indicate some of them:

- may be it considered useful or didactically correct to point a priory the intuitive necessity of the introduction of a new variable?
- what can we say about the mental representation of students about the process/state approach to phenomena: are they always intermixed or one may be predominant on the other?
- what about a mainly macroscopic approach to thermodynamics as contrasted with a mainly statistical approach?
- what about a didactical presentation of entropy from a positive (optimistic if you like) point of view as contrasted with traditional negative presentation always in terms of "disgregation" "disorder" "death of the universe"? After all our same existence as living beings is the result of evolution in a world which needs entropy to be described.

P. Thomsen's "Sporg Naturen"

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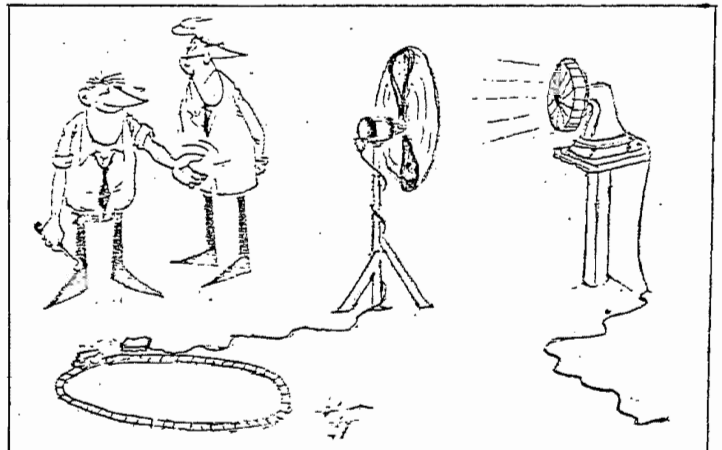

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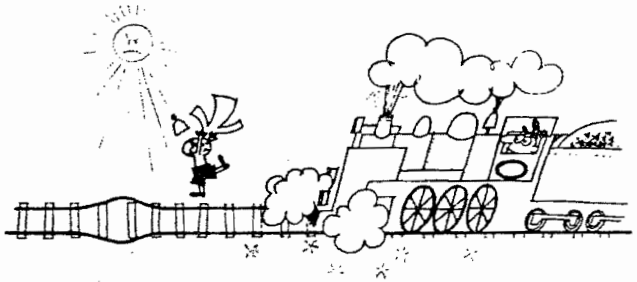
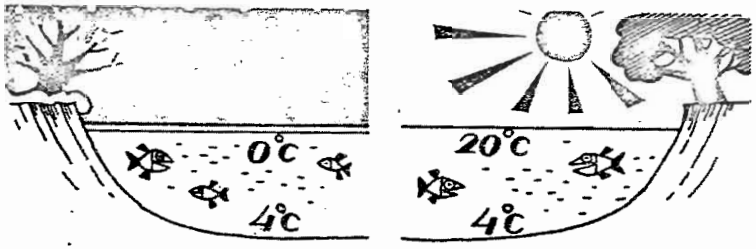


Kiskot saattavat kuumalla ilmalla laajeta niin paljon, että vääntyvät.

THERMAL DILATATION



from "Ylaasteen fysiikka ja kemia" for grade 7-9
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ÚSTŘ... AKADEMIE...

STATISTICS

M. TYC. AKADEMIE KNIHOVNA
Sig. 462 / 84 sv.

THERMODYNAMICS IS NOT ONLY A THEORY FOR HEAT, BUT IT IS THE FOUNDATION OF PHYSICS.

G.Falk

THE SECOND LAW OF THERMODYNAMICS HOLDS - I THINK - THE SUPREME POSITION AMONG THE LAWS OF NATURE.

Sir Arthur Eddington

IN THE GAME OF ENERGY AND THERMODYNAMICS YOU CAN'T EVEN BREAK EVEN.

Isaac Asimov

THE KINETIC THEORY OF HEAT MIGHT BE SAID TO BE WORKING OUT THE CONSEQUENCES OF ONE SIMPLE PRINCIPLE, NAMELY: MOLECULES ARE BLIND. OR, IF YOU PREFER: MOLECULES DON'T CARE.

Jon Ogborn

WHENEVER THERE IS A GREAT DEAL OF ENERGY IN ONE REGION AND A VERY LITTLE IN THE NEIGHBOURING REGION, ENERGY TENDS TO TRAVEL FROM THE ONE REGION TO THE OTHER, UNTIL EQUALITY IS ESTABLISHED. THIS WHOLE PROCESS MAY BE DESCRIBED AS A TENDENCY TOWARD DEMOCRACY.

Bertrand Russell

L'ESPRIT VA DANS SON TRAVAIL, DE SON DÉSODRE, A SON ODRE. IL IMPORTE QU'IL SE CONSERVE JUSQU'A LA FIN, DES RESSOURCES DE DÉSODRE, ET QUE L'ODRE QU'IL A COMMENCÉ DE SE DONNER NE SE LIE PAS SI COMPLEMENT NE LUI SOIT PAS UN SI RIGIDE MAITRE, QU'IL NE PUISSE LE CHANGER ET USER DE SA LIBERTÉ INITIALE.

Paul Valery

ENTROPY ARGUMENTS IN THE TEACHING OF CHEMISTRY AND PHYSICS

Jon Ogborn

Chelsea College, Bridges Place, London SW6 4HR, England

1. INTRODUCTION

A long-standing personal interest in statistical thermodynamics, and in the possibility that ways could be found to lay bare some of its simple essence, led a decade ago to work in the Nuffield Advanced Physics course, published as Unit 9 Change and Chance of that course. Recently, stimulated by discussions with those revising the Nuffield Advanced Chemistry course, I have been led to rethink and extend a number of ideas, and it has been suggested to me that teachers of Chemistry and Physics, though primarily the former, might find it useful to have this collection of simple approaches to the fundamental ideas of statistical thermodynamics.

The various approaches suggested here do not form a single teaching package. Any given course must necessarily select, in the light of other pressures on time, a more limited view than the sum of those offered here. At the same time, the wider perspective offered by a number of different, sometimes competing approaches, may have value for the teacher in helping to place that which is actually taught in a larger setting, in providing alternatives when a chosen approach presents difficulties, and in adding something to the teacher's own grasp of the fundamentals.

Nevertheless, the approaches suggested here do have a certain consistency. All are premised on the view that, despite the merits of a model-free macroscopic thermodynamics, a molecular picture - and so a statistical one - is likely to make more sense to pupils when they begin the subject, and to aid any further study they make by giving them a sense of understanding the content of such concepts as entropy and free energy, rather than merely a knowledge of certain relationships between such quantities. Too often even the best students confess to a sense of unease about what entropy, or free energy, actually 'is' and so to a sense of detachment of the theory from reality. In general, also, the arguments offered treat only very simple cases, with the intention of laying out the basic nature of the argument rather than its full application to more complex cases of interest.

It is all too easy to offer high level points of view, in this area, but to fail to find or illustrate the kinds of words or examples which might actually connect with pupils' previous understanding. Thus, at some risk of excessive length and of encroaching on the teacher's own preserves, some attempt has been made to suggest how the various approaches might be presented to a class. The style and language will not suit everybody, but it is hoped that these sketches will at least suggest how the ideas might be put to students.

2. OVERVIEW

This section describes briefly the organisation of the rest of the paper. It is to be regarded as a kind of jigsaw puzzle, put together here in a certain way, but able to be taken to pieces and put together again in other ways.

Section 3 introduces the idea of entropy, with qualitative illustrations of the idea of counting different states for a variety of kinds of physical system.

Section 4 gives a first simple example of actually counting numbers of states, or rather changes to numbers of states, for a primitive model of an ideal gas. A value of an entropy change is calculated, and the expression for the dependence of entropy on pressure obtained. Section 5 shows briefly how these ideas might be exploited in a preliminary account of the concept of free energy.

Section 6 is the heart and crux of the discussion: it tackles the question of how to count ways of arranging particles at different energies, working towards the meaning of the thermal contribution to entropy and entropy changes. Like Section 3 it uses very little mathematics, and develops ideas through random simulation games. Results are a statistical definition of temperature, entropy change in terms of energy and temperature, and the basic idea behind the Boltzmann factor.

Section 7 briefly shows how the ideas of Section 6 can be used to develop the Einstein model of solids. Section 8 discusses the Boltzmann factor, as it might emerge from Section 6 or from some alternative arguments. It is here that the results begin to bring dividends in terms of practical applications.

Section 9 examines some patterns in numerical values of entropies, trying to understand and interpret them in the light of the previous ideas.

Section 10 begins the discussion of chemical equilibrium by considering how to make reactions go in the desired direction. Section 11 returns to free energy to show how that is another way of looking at entropy change, and so at the direction of a reaction.

Section 12 now considers equilibria, in the case of gas reactions, showing how to put together ideas from several previous sections, arriving at the expression for the equilibrium constant in terms of the standard free energy change.

Section 13 parallels Section 12, now considering the effects of concentration on entropy changes in solution, leading to a discussion of potential differences available from ionic reactions, and expressions for the equilibrium constant.

3. ENTROPY AND NUMBER OF ARRANGEMENTS

Since Boltzmann, it has been possible to say clearly what entropy is, namely the scaled down logarithm of the number of ways of arranging the particles of a system, including the energies they have, which leave its large scale properties, such as how hot it is or what pressure it has, unchanged. Thanks to quantum mechanics, the simple idea that all we have to imagine doing is counting possible states of the system works for the energies of particles as well as for more obviously countable arrangements such as spatial positions. Thus we can say directly, and preferably rather early in a course, that entropy has to do with counting.

Clearly, one needs examples to illustrate the idea, and reasons why counting states of a system might be an important thing to do.

One of the clearest examples, though not particularly chemical in tone, is defects in solids, simply because the particles are easily imagined firmly arranged in space. Such defects matter, for example in influencing the likelihood of a pressure vessel in a chemical plant bursting, or in helping determine the colour of some minerals (F-centres). Thus, one might say, suppose a few particles are missing from a crystal lattice. If the number which are missing, rather than just which sites happen to be vacant, is what matters, we can imagine counting all the different pictures of the lattice that could be drawn with just that total number of empty sites. If there is just one defect, it could be at the place of any one particle in the perfect crystal, so there are as many pictures as particles. If there are more than one, the counting is harder but still possible to imagine, at least in terms of drawing all possible pictures. In the sketch (Figure 1) there are 30 sites and two defects: one defect could be in 30 places and the other in one of the remaining 29, giving 30 x 29 pictures. Figure 1 shows two of those pictures, because it doesn't matter which empty site was chosen first. So there are 30 x 29 /2 = 435 pictures. The number of ways of arranging vacancies amongst lattice sites contributes to the entropy of an imperfect crystal.

Less easy to be definite about, but nearer home to the chemist, might be the entropy associated with substances in solution. One can easily imagine solute particles jostling about, exchanging places with solvent particles. A glass of salty water tastes just as salty no matter just where the two kinds of particles find themselves, and we can again at least imagine drawing all possible pictures like Figure 2(a) , making exchanges between solvent and solute particles.

A more complete story would have to take account of where the particles were, and in reality, of tendencies such as the clumping of ions in solution around (say) polar water molecules. Nevertheless, the number of ways simply of exchanging places between solvent and solute particles makes a contribution to the entropy of the solution at given concentration, and indeed turns out to help in understanding the concentrations at which reactions in solution reach equilibrium.

Another simple example is a magnetised solid. If the solid is strongly magnetised, molecular dipoles line up more or less along the applied magnetic field. If it is less strongly magnetised, some point in

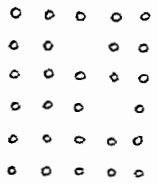


Figure 1 Defects in a solid.

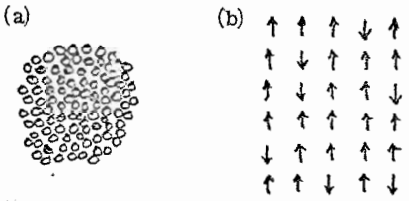


Figure 2 (a) solvent and solute (b) magne

Figure 3 Chains in rubber (a) stretched (b) unstretched

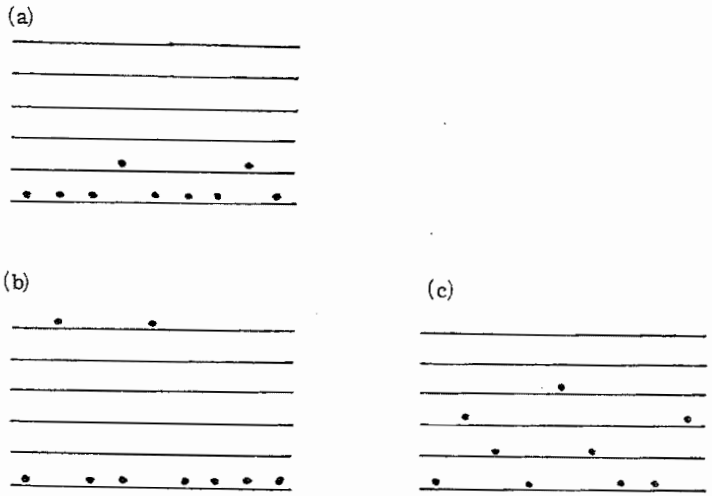


Figure 4 Particles on energy levels (a) most at low energy (b) a few at high energy (c) several at intermediate energies

other directions: for a simple picture we might imagine them pointing oppositely as in Figure 2(b). It is not hard to see that there are fewer possible choices of which dipoles point which way when most point one way; and that the number of possible pictures increases as the total numbers pointing each way become more equal. The number of ways of arranging how dipoles point contributes to the entropy of the magnetised solid, and is important in reaching and in measuring very low temperatures.

A more homely example of entropy to do with pointing is a rubber band. Rubber consists of chains of linked isoprene molecules, free to rotate (rather like a Rubik snake) about some of the C-C joints in the chain. If such chains are cross-linked at intervals (by S atoms introduced in the vulcanising process) we get a rubber. Stretched taut, the chains are as extended as they can be without deforming covalent bonds: that is, the snakes run straight as in Figure 3(a). Relaxed somewhat, some links in chains can point in various directions, as in Figure 3(b). Clearly there are more choices of which links point which way when the rubber is relaxed, and links point in many directions. The number of ways of arranging the path of a chain between cross-links contributes to the entropy of the rubber, and helps to determine some of its properties, such as the fact that it gets warmer when suddenly stretched.

Many of the spatial examples mentioned involve energy changes, and indeed it is entropy changes associated with changes in energy which turn out to be the most important problem we have to deal with in understanding chemical and physical change from a molecular point of view. Thus a defect in a solid lattice will generally strain the lattice, particles in a solvent will generally have energy associated with forces between the molecules, and dipoles in a field have energy associated with the forces on them from the field and from one another.

The way energy is counted in is to ask at what possible energies the particles of the system could exist, making some picture like Figure 4. If the object in question is very, very cold, say in liquid helium, most of its particles will occupy the lowest possible energy level. If it is warmer, more will be at higher levels, and there is an entropy associated with the number of different pictures we could draw for any given total energy. There could be a few pictures with a few particles at very high levels (b), and many more with most particles at more moderate energies (c). Adding energy will lead to more possible pictures, and so to a greater entropy. Since adding energy can warm things up, it is not surprising that there is a fundamental link between entropy and temperature.

So far, we have illustrated what counting numbers of ways might mean, but not why it might matter.

The reason we count numbers of ways in which particles and their energy can be arranged is, at bottom, that the particles don't care how they are arranged. Faced with an exploding firework, it is easy to imagine that the explosion 'wants' to go: that the molecules are in some way eager for it to happen, and cooperate to that effect with the chemist. But this is absurd: molecules, whether rushing outwards

as a gas in an explosion or condensing from water vapour into drops on the kitchen window, are just particles in motion, getting re-arranged. There can be no explanation like that we might give for people crowding together at a football match, in terms of wishes or intentions. The answer is to give up the attempt: one has to say that all physical or chemical change happens by the random re-arrangement of molecules and energy. **The molecules don't care**; the job of the chemist is to get them to do what the chemist wants, without their co-operation. The wonder is that chemistry is possible at all, and it is arguments about the numbers of ways of arranging molecules that shows why it is.

The argument, in outline, goes like this. By 'random' we mean that a system tries out all the possibilities open to it, without favouring one more than another. Nothing guides which state it is in, except chance, and so sooner or later it occupies all the states which are possible. Some states are not possible – perhaps they imply more space to move about in or more total energy than there is. But suppose we change the conditions, say increasing the volume available to a gas. Sooner or later the gas fills the new volume, without our having to tell the molecules that there is more space – they simply find it by random motions which sometimes move a molecule into the new region. For the same kind of reason, a crystal of salt put in water dissolves, and the ions diffuse to occupy the whole solution rather evenly. Those changes which happen, of and by themselves, are those in which a system evolves so as to occupy all the arrangements open to it.

The obvious examples, like expansion or diffusion, are easy to see, but each such obvious case has its converse. Gases can be compressed, solutions can be concentrated, salts can be precipitated. Even muddy water left to stand may become clear. Here we need what is perhaps the most fundamental principle of chemical change: **no change happens in both directions under identical conditions.** Now one way to get a gas to contract is to cool it: to provide cold surroundings into which some of the energy of the gas passes, again completely at random. What has been done is again to change the conditions, here to allow energy to 'diffuse' out from the gas, so that the system, now counting in the cold surroundings, again changes in such a way as to find all the possibilities open to it.

These are the reasons why we count numbers of ways of arranging molecules. Just suppose that in some instance we could succeed; that we knew the number of ways W in which, let us say, the ions in a given solution could be arranged amongst the solvent molecules, counting in also the energies that each kind of particle could have. Then the entropy S of this solution would be given by

$$S = k \ln W$$

k being the Boltzmann constant.

The entropy is just another way of looking at the number of ways W. k is no more than a convenient choice for a scaling constant, and we shall see reasons in the next section why k is particularly convenient and why we trouble to take the logarithm of W.

The most fundamental property of entropy is that it never decreases. Clearly, if a system is to evolve on its own, it must find new states to be in, new ways of arranging its parts. So for any change that happens, W increases. If nothing happens, W stays the same. But it is not possible that molecules, blindly trying out all possibilities, happen for no reason to retract from trying out some of those accessible to them (except for brief random fluctuations). So W never decreases, and nor does the entropy S.

The sections which follow show how all this works out in different kinds of examples. They show different ways in which entropy changes arise, how in principle to calculate them, how to get round the practical impossibility of actually counting W (especially when the number of pictures one could draw of quite simple systems would need more sheets of paper than there are atoms in the Universe!), and how a chemist can use entropy changes to guide the choice of conditions in which a reaction will go – even though by blind random uncaring molecular shuffling – the way the chemist wants.

4. COUNTING WAYS FOR A GAS

An opportunity for introducing entropy changes, and possibly a first look at free energy, occurs when one has discussed the kinetic theory of gases. Indeed the kinetic theory itself is a good example of the principle 'the molecules don't care', in that the equation of state is obtained just from random molecular motion and impact.

Figure 5 shows a model of diffusion, with particles spreading from one half of a box into the whole space, by random collision. Simulations with ball bearings in a tray are not too difficult. A computer program doing all the Newtonian calculations is likely to run very slowly, except possibly if in machine code.

For most of us, dice are the concrete representation of chance, so it is useful to see how pure chance replicates the effect of the random collisons. Consider the dice game shown in Figure 6(a).

Six counters, each numbered, are put in one half of a tray. Then a die is thrown and the counter whose number comes up is moved to the half of the tray it is not presently in. On the first throw, a counter must move, but no one can say which. On the second, a second counter is likely to follow it, but just sometimes the first to move will go back. As the game continues, most often counters are spread evenly between the two halves, but it can be that they all go back into one half.

If we drew all possible pictures showing counters in one half or another, how many would there be? Tear a large sheet in two, one for all the pictures with counter 1 on the left and one for that counter on the right. Now tear the first in two, for all with no. 1 on the left and no. 2 on either the left or right. Repeat for the sheet with no. 1 on the right (Figure 6(b)). To have one sheet for each picture we have to tear all the sheets in two, six times in a row.

Since the two possibilities for each counter go with the two for every

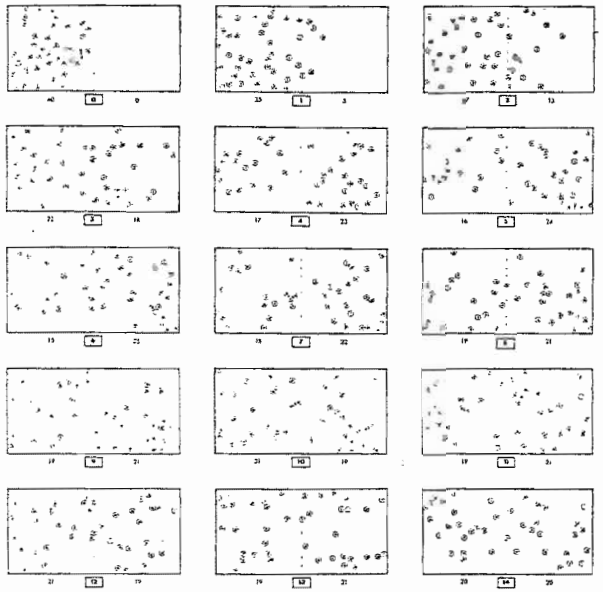


Figure 5 40 particles diffusing across a box (from Reif F, Statistical Physics, McGraw-Hill 1964)

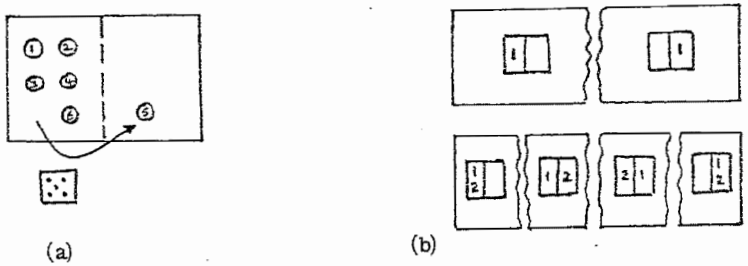


Figure 6 Six particles in a box (a) a possible first move (b) tearing sheets to draw all possible arrangements.

other, we need

$$2 \times 2 \times 2 \times 2 \times 2 \times 2 = 2^6 = 64$$

sheets for the 64 possible different pictures.

Nothing was said about where to put the counters in each half. Suppose that each half was divided into (say) 20 small squares. If you had a 20 sided die you could decide where by chance to put a counter inside the half it was to go into. At the start, there were 6 counters all in one half. They could be put there in

$$20 \times 20 \times 20 \times 20 \times 20 \times 20 = 20^6 = 64 \text{ million}$$

ways. When allowed to pass between both halves, there are 40 places for them to go, so that the number of different pictures is now:

$$40 \times 40 \times 40 \times 40 \times 40 \times 40 = 40^6$$

But we can write this last number as

$$\begin{array}{l} 20 \times 20 \times 20 \times 20 \times 20 \times 20 \\ \times 2 \ \times 2 \ \times 2 \ \times 2 \ \times 2 \ \times 2 \end{array}$$

or as $40^6 = 20^6 \times 2^6$.

By opening up the second half, the number of ways has been multiplied by 2^6. This remains true however we might have chosen to divide up the halves into smaller pieces. Thus doubling the space available to N particles multiples the previous number of ways W by the factor 2^N, if all the space is equally likely to be occupied and the position of any one particle has no influence on the position of any other.

What if there were 100 counters? Writing W_1 and W_2 for the numbers of ways before and after doubling the volume,

$$W_2 = W_1 \times 2^{100}$$

A calculator shows this to be about 10^{30}. Even if a computer shuffled the counters a million times a second, to try all the possibilities would take 10^{24} seconds. People reckon that the Universe is around 10^{10} years old, which is 'only' $3\ 10^{17}$ seconds, so we can be sure it would still be trying. Now the special case of all in (say) the left hand side is just one amongst 2^{100} possibilities, so that if we start in some other state we must expect to spend a long time waiting for that special state to occur. A spontaneous collapse to half the volume is unlikely.

For one mole of gas, the numbers are more startling and even less imaginable. With $N = 6\ 10^{23}$ we need to know what

$$2^{(6\ 10^{23})}$$

looks like. We know that $\log 2^3 = 3 \log 2$, so

$$\log 2^{(6\ 10^{23})} = 6\ 10^{23} \log 2 \approx 2\ 10^{23}$$

since log 2=0.3. Now the log of a number (base 10) is just the number of zeroes in it if we write it out in ordinary place notation. So the big number we want is 1 followed by $2\ 10^{23}$ zeroes. Even if we wrote it in numerals the size of atoms, 10^{-10} m across, it would occupy $2\ 10^{13}$ m, which is more than 100 times the distance to the Sun.

Thus we reach an important conclusion. The 'reason' why gases diffuse into empty space is just that it is overwhelmingly likely to happen by chance alone.

We can also see some sense in using the logarithm in $S = k \ln W$, since

$$W_2 = W_1 \times 2^N$$

$$\ln W_2 = \ln W_1 + N \ln 2$$

and the change in entropy

$$\Delta S = S_2 - S_1 = k (\ln W_2 - \ln W_1)$$

$$= k N \ln 2$$

For $N = 6\ 10^{23}$, and $k = 1.4\ 10^{-23}$ J K^{-1}, since ln 2=0.7, we get

$$\Delta S = 6 \text{ J K}^{-1}$$

This is a first calculation of an entropy change from first principles. Because the entropy is found from the logarithm of W, when W is multiplied by some factor, a certain amount is added to the entropy. We do this just because, as we saw above, numbers of ways do multiply, since they arise from combining possibilities which exist independently.

If we now take the application to gases more seriously, we can see some sense in the use of the Boltzmann constant k, and get a hint of the importance of a quantity called the free energy. It is important to realize that these simple ideas cannot strictly apply to a gas, because there is no way, even in imagination, that gas molecules can be thought of as identifiable. Thus a die could not 'know' which molecule it had picked on. However, in a gas at a suitable pressure, the molecules are rather far apart, and this has the effect of making them behave very much as if we could tell them apart. There is, however, no simple reason one can offer for this. The values of W_1 and W_2 change drastically because molecules are not identifiable, but it stays true that their ratio is 2^N for a doubling of the volume of N molecules of an ideal gas.

In the numerical example, the number 2 was just the ratio of volumes after to that before, and we can replace it by the volume ratio V_2/V_1, raised to the power N. This gives

$$\Delta S = k N \ln (V_2/V_1)$$

for any volume change if the temperature remains constant.

Change in entropy is just the logarithm of the factor [here $(V_2/V_1)^N$] by which the number of ways W is multiplied, scaled down by the factor k. If we wish, we may speak of the entropy of objects, though this usually means some arbitrary choice of zero. For example, the entropy of one mole of He at atmospheric pressure and at 298 K is

$$S^\theta = 126 \text{ J K}^{-1} \text{ mol}^{-1}$$

and such standard values are tabulated for many substances. To use such entropies, for example in trying to decide if a gas reaction will go under given conditions, we need to be able to find the entropy at other than standard conditions. From the previous arguments, we know that the entropy of He at half an atmosphere is just 6 J K^{-1} mol^{-1} more than the above value, and that at two atmospheres it is 6 J K^{-1} mol^{-1} less than the standard, because the first change doubles the volume and the second halves it.

In general, given the entropy at standard pressure p^θ, we want its value at another pressure p. At the same temperature; writing V_1 for the volume at p^θ and V_2 for the volume at p:

$$p/p^\theta = V_1/V_2 = 1/(V_2/V_1)$$

Thus $\ln (V_2/V_1) = -\ln (p/p^\theta)$ and we can write the entropy change as

$$\Delta S = S - S^\theta = -k N \ln (p/p^\theta)$$

or

$$S = S^\theta - k N \ln (p/p^\theta)$$

The minus sign says that the entropy goes up as the pressure goes down, simply because at lower pressures the molecules occupy a greater space. This result is very valuable, because in a mixture of gases possibly taking part in a gas reaction, we can use the partial pressures p of each component to calculate entropy changes for that component.

To write down such standard entropies means that someone claims to know how to count the total number of arrangements of helium atoms in a given volume. It can be done (the nature of the argument is sketched shortly), but is far from easy. More often entropies are measured, and we shall later see in principle how.

Another important result, this time between entropy and energy, can also be obtained. Since $\ln(V_2/V_1)$ is just $\Delta \ln V$, the change in the logarithm of the volume, we have

$$S = k N \Delta \ln V$$

Suppose the change is very small, so that we write in the limit

$$dS = k N d (\ln V)$$

A calculator shows rather clearly that d (ln V) is the same as the fractional change dV/V: indeed this is just what the logarithm

function is designed to do. Try for example ln 1.001 − ln 1.000.

Thus for a small change dV (Figure 7),

$$dS = k\,N\,dV/V$$

and we know that

$$P = k\,N\,T/V$$

so we see at once that the work PdV is

$$P\,dV = k\,N\,T\,dV/V = T\,dS$$

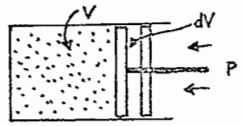


Figure 7
Gas expanding against a piston.

In the ideal gas equation the scale of T is arbitrary. If the absolute scale were changed, the value of k would change. Thus the effect of using k in the definition of entropy k ln W is to ensure that in such cases T dS is not merely proportional to an energy change, but equal to it.

In such an isothermal expansion the gas gains or loses no internal energy (if the molecules have no significant attraction forces) and the energy balance is kept by a thermal flow of energy into the gas from the surroundings. The thermal exchange of energy q must be equal to the work done, so we also have:

$$dS = q/T$$

a result of far greater general importance than this simple argument would suggest.

[Some remarks, exclusively for teachers, about the real nature of the difficulty of applying a model of distinguishable particles in boxes to a gas, are perhaps here in order. The calculation of numbers of ways W for a gas in a box goes somewhat as follows. In one dimension, a molecule confined in a 'box' of length d can be thought of as a de-Broglie standing wave, of wavelength λ . If the standing wave has n loops then

$$d = n\lambda/2$$

and since $mv = h/\lambda$, the kinetic energy of the molecule is given by

$$E_k = (mv)^2/2m = n^2h^2/8md^2$$

For d = 0.1 m, with hydrogen atoms,

$$E_k = 3\ 10^{-39}n^2$$

Thus the change in energy in going from n=1 to n=2 is about 10^{-38} J, or about $2\ 10^{-18}$ times kT, and it is clear why energy changes in a gas can be treated as essentially continuous. The effect is even stronger in three dimensions. Equally, if the energy is near kT, as it is, the molecule must be in a state of very high n, so that a jump to n+1 is imperceptible as a discrete jump.

The upshot is that a gas must be modelled as having an enormous number of very finely spaced energy levels, indeed with more levels than molecules in an energy range comparable to kT. One has to group levels together, and then count numbers of ways of distributing the molecules amongst the levels. If the box expands, the levels get even closer together, so that there are more in a given range of energy, and more ways of arranging molecules amongst them with the same total energy.

We have therefore obtained a correct result by an argument which is not of the right kind for actual gases, though it would apply correctly to collections of distinguishable particles, such as dust grains. What is right about it is its statistical character, and it may be valuable just for that, despite these necessary reservations.]

The previous statistical shuffling argument says two difficult things at once: that the statistics works from an assumption that all arrangements are equally possible, but concludes that some kinds occur so rarely as never to be seen. It may therefore help to bring out the fact that statistical fluctuations can and do happen. One such example has to do with why the sky is blue.

Part of the reason (in addition to light scattered off molecules themselves) why the sky is blue is that on a scale comparable to the wavelength of light, there are few enough air molecules in the atmosphere for appreciable density fluctuations to occur, from which light is scattered. A 'box' one visible wavelength on a side would contain some three million molecules at atmospheric pressure, and fewer high in the atmosphere. A 'box' of one tenth that dimension would contain some 3000 molecules. Since

$$d\,(\ln W) = N\,d\,(\ln V)$$

or

$$dW/W = N\,dV/V$$

for small variations, we can get a rough idea of what sizes of fluctuations are likely. If dW/W is small, the change in volume hardly alters the number of ways, so that fluctuations with dW/W about 1/10 will be not infrequent. That would put dV/V or the fractional density change at about 1/300 for N = 3000. Larger fluctuations would occur, but less often. Clearly then, at a scale not much less than the wavelength of blue light, fluctuations big enough to scatter light appreciably are going to happen. The result is that blue light is scattered more than red, and we see a blue sky and red sunrise and sunset.

5. A FIRST LOOK AT FREE ENERGY

We have, without noticing, calculated in the previous section a quantity which chemists call free energy. When a gas doubles its volume, there is an entropy change of the gas equal to

$$\Delta S = 6\ J\ K^{-1}mol^{-1}$$

which has this value regardless of whether the gas diffuses into an empty volume, or expands against a piston. The entropy change is decided just by the ratio of initial and final volumes. However, if we do arrange for the gas to expand against a piston, we can get it to do work as it expands, and the work we can get is given by

$$-T\Delta S = -1800 \text{ J mol}^{-1}$$

if the temperature happens to be 300K. The minus sign says, on the usual chemical convention, that the gas delivers this energy. The internal energy of the gas itself is not changed at all by such an expansion, so it is wrong to think of the work as taken out of the gas. It comes from the process of doubling the volume, and is replaced in the gas by a heat flow from the surroundings. To get this work, cylinders and pistons have to be contrived, and if they are not provided, the gas may deliver less, or even no work in expanding. What $-T\Delta S$ tells us is the most work we can get by any contrivance.

This is the quantity called free energy change. It is not to be thought of as a special part of the energy of the gas which is 'free', the rest being 'unfree'. Indeed, in the present case, the energy of the gas is unchanged. The free energy change is associated simply with the change of state of the gas, under given conditions (here constant temperature, implying some kind of constant temperature surroundings). Nor is free energy cheap: to obtain the work which can be obtained generally needs some costly device.

Chemists are not particularly concerned with work that can be extracted from a reaction, but rather with the chemical products. The importance of free energy to a chemist is that it is another way of talking about entropy changes, and so another way of asking whether a desirable reaction will go. Its meaning has to do with work simply because work is the name we give to an energy transfer which involves no change in entropy. We can always have less work, and let the entropy increase more, but we can't have more than the free energy change allows.

These remarks will be elaborated later when we have considered entropy changes involved in energy transfer. It will then emerge that what is commonly called 'energy' in discussion for example of fuel resources, is probably closer to the concept of free energy than it is to the scientific concept of energy.

6. COUNTING ENERGY STATES: TEMPERATURE

The arguments so far have at best only just touched upon the central problem, namely the entropy changes associated with exchanges of energy. Some teachers may be content to develop the argument of section 4 to show that for isothermal volume changes of an ideal gas

$$\Delta S_{gas} = \Delta H_{gas}/T$$

so that if the change is reversible

$$\Delta S_{surroundings} = -\Delta H_{gas}/T$$

and to apply this to chemical systems in general, writing

$$\Delta S_{total} = \Delta S_{surroundings} + \Delta S_{system}$$

and at constant pressure

$$\Delta S_{total} = -\Delta H_{system}/T + \Delta S_{system}$$

and even $$\Delta G = -T\Delta S_{total} = \Delta H_{system} - T\Delta S_{system}.$$

This line of argument is brief but does not illuminate why the entropy of the surroundings alters when energy is given to it or taken from it. Indeed, a quite falsely balanced picture of entropy changes may thus be given, associating them more with configurational than with energy changes. For these reasons, the following kind of discussion ought at least to be considered.

In teaching about atomic structure, one is likely to have made the point that energies of atoms and molecules are quantised. Evidence, for example from collisions or from spectra, may have been presented. Calculating what discrete energy states are available is difficult, but for the present purpose we need only the fact of discreteness.

Consider, merely for simplicity, a set of equally spaced energy states or levels as in figure 8, like rungs of a ladder, or floors in a building. One particle is shown on the "second floor".

In fact, such a system can be interpreted as the levels of a harmonic oscillator (in which case the energy interval $\varepsilon = h\nu$). There is no need to offer such an interpretation now, however.

If two such particles share four units ε of energy, then Figure 9(a) shows one possibility, and figure 9(b) another.

How many possibilities are there altogether? There are five:

particle A	particle B
0	4
1	3
2	2
3	1
4	0

Now add one more unit of energy. There are now six possibilities:

particle A	particle B
0	5
1	4
2	3
3	2
4	1
5	0

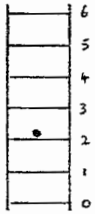


Figure 8 One particle on a set of levels

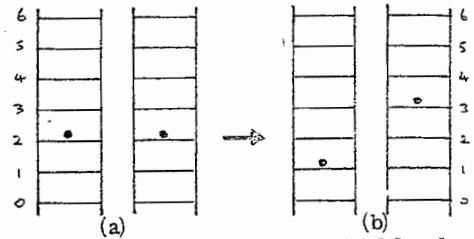


Figure 9 Two particles on a set of levels (a) one arrangement (b) another

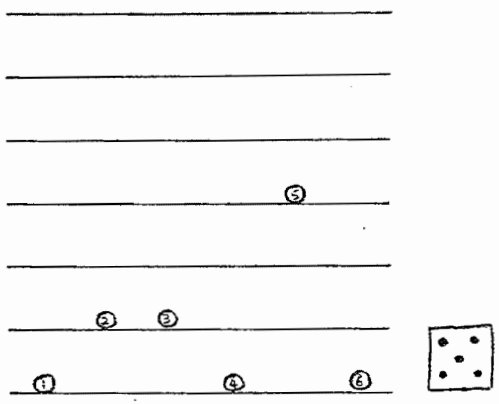


Figure 10 Counters on levels

Giving more energy leads to more arrangements, and so to more entropy. However, if we start with little total energy, say 2 quanta shared between two particles, then the 2 arrangements become 3 when a quantum is added, multiplying W by 3/2, whilst if we start with 100 quanta shared between two particles, adding one more quantum multiplies W by only 101/100. The entropy increase for a given energy added depends on how much energy is already there.

Calculations are harder for more than two particles, and the number of arrangements increases rapidly. For 10 particles sharing 10 quanta there are W = 92378 arrangements, and adding one more multiplies this by 20/11. For 100 particles sharing 100 quanta there are W = 8 10^{59} possibilities. [W = (N-1+n)!/(N-1)!n! for n quanta shared amongst N oscillators. See Section 7.]

The point at present is that particles can arrange themselves amongst energy states in many ways, and that adding to the total energy increases the number of ways, while removing energy decreases it. It is for this reason that heating an electric kettle full of water increases its entropy. Such entropy changes are important in many chemical reactions, notably explosions in which the surroundings are given energy and become hot.

A picture of random exchanges of energy

It often helps, with a new idea - in this case arrangement and re-arrangement of particles amongst levels - to get a picture of what it means. This can be done, both with a simple game played with counters and dice, and with a computer simulation.

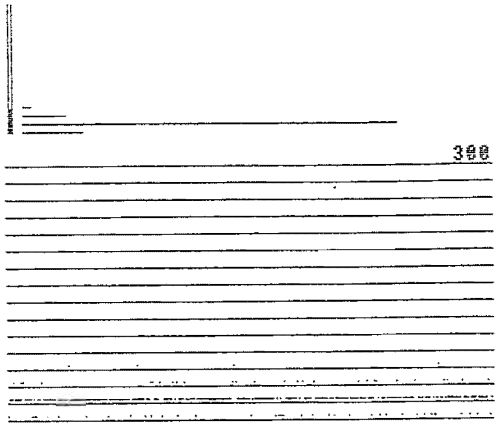
For a game played by hand, counters representing particles are moved up and down a ladder of levels as in Figure 10. Moves are made by choosing one particle at random to be moved down one level, and doing so if it is above the lowest level (if not, try again). Then, conserving energy, a particle is again chosen at random and is moved up one level. As the game continues, a record is kept of the number of particles at each level.

(The random choice can be made for n particles with an n-sided die. n = 20 is good. Alternatives, such as using random numbers, drawing cards from a hat, spinning a top marked with a value for each particle, or using a computer to decide which particles to move can all be satisfactory.)

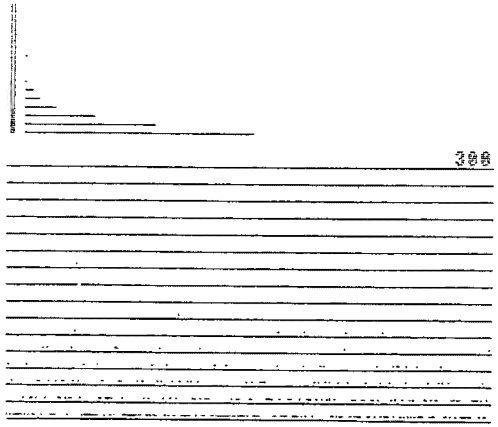
Computer versions able to use some hundreds of particles have been programmed (one will be published with the Nuffield Advanced Physics materials). It is important for the display to show both the particles on the levels, and the current distribution of numbers on levels.

Figure 11 shows such a display, with 300 particles, (a) near the beginning of such a shuffling 'game', and (b) after many moves.

The key result is that the distribution finally fluctuates about an exponential distribution, that is, that the number of particles in a



(a)



(b)

Figure 11 300 particles on energy levels
(a) soon after starting with all on one level
(b) after a considerable number of moves

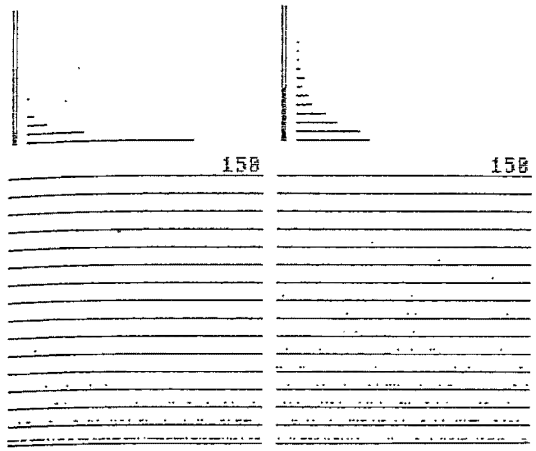


Figure 12 Two isolated systems, with different energies per particle

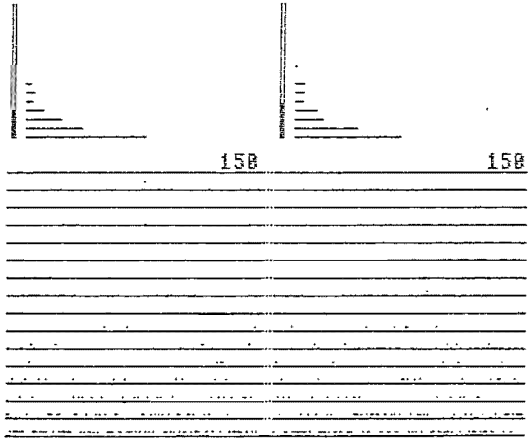


Figure 13 The two systems of Figure 12, in contact and nearing equilibrium.

given level bear a constant ratio r to the number in the next higher level. A programme which averages distributions over a period of time shows the exponential distribution even more clearly than Figure 11 (b).

Figure 12 shows the result of shuffling two such systems independently, one having more energy per particle than the other. Both distributions fluctuate around an exponential form, but the one with more energy per particle has the smaller ratio r. That it is energy per particle which determines r can be seen by varying the numbers of particles in the two systems.

Temperature

Informally, one wants to say that two such systems as in Figure 12 have different temperatures. However, more fundamentally, the behaviour of such systems can be used to introduce and define a temperature, on a microscopic basis. First, when two such systems are joined, and particles shuffled as if they belonged to one, the two distributions become more and more similar as in Figure 13, with energy passing from one to the other until equilibrium is reached. The direction of the temperature difference is now clear: energy flows thermally from hotter to colder. This thermal flow happens, as does diffusion, entirely by chance. It is systematic because movement in the favoured direction increases the total number of arrangements in the combined system.

Temperature can now be given a microscopic definition, by arguments at various levels of sophistication. A simple argument says that the energy flows from the part with a small ratio r to the part with a large ratio, until r becomes equal for both. Temperature T should thus be inversely related to r. If we wrote

$$T \propto 1/r$$

then since r tends to 1 as more and more energy is added, and becomes large if there is little energy, temperature would range from zero (cold) to unity (hot). The solution actually chosen by chemists and physicists is to define

$$kT = \varepsilon / \ln r$$

that is, to make T proportional to the constant slope of a logarithmic plot of the distribution (Figure 14). k is chosen to be the Boltzmann constant, scaling temperature in terms of energy ε.

Since ln(1) = 0, this allows high temperatures to go towards infinity, but preserves the same zero. This relation between temperature and the microscopic quantity r is more familiar in the form:

$$\frac{\text{no. of particles in higher level}}{\text{no. of particles in lower level}} = 1/r = \exp(-\varepsilon/kT)$$

This simple line of thought conceals the true rationale for defining

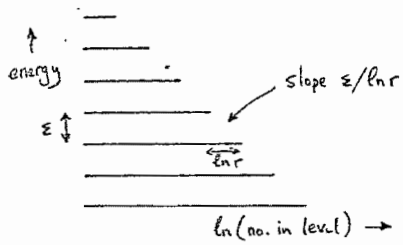


Figure 14 Logarithmic plot of equilibrium distribution

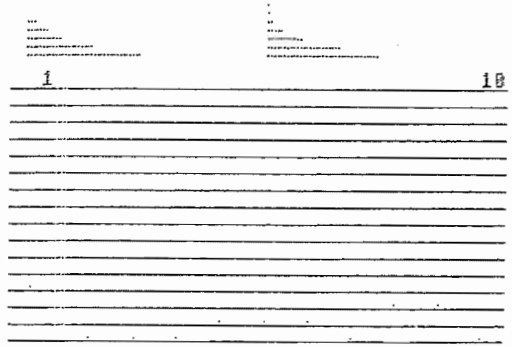


Figure 15 One particle sharing energy with ten others, showing time averaged distributions.

T, however. This is that temperature should be related to the change in the number of ways of arranging particles on levels when energy is added or removed. The microscopic reason why thermal flow of energy is from hot to cold has already been shown in the simple examples of counting arrangements given before. Adding energy to a cold object multiples W by a larger factor than that which divides W when energy is taken from something hot. Since

$$W_{total} = W_{cold} \times W_{hot}$$

if W_{cold} increases by a larger factor than that by which W_{hot} decreases, W_{total} becomes larger, and this is the direction of the random process. Temperature thus originates in the almost obvious idea that adding energy increases the number of arrangements, together with the less obvious idea that the magnitude of the increase depends on how much energy is already there.

Now the ratio r, introduced as the ratio of numbers of particles in adjacent levels, has a deeper interpretation in this connection. It is simply the factor by which W increases when one quantum is added to the system (or by which W is divided when one quantum is taken away). That this is so can be seen by considering just <u>one</u> particle, sharing energy by random shuffling with a larger number, as in Figure 15.

If the single particle happens to fall one level interval ε, one quantum of energy ε is shared amongst the rest. This increases W for the rest by some factor, and so such an event happens more frequently than not. For the lone particle to gain energy, it must acquire it from the rest and this decreases W, so happening rarely. This is why on average (Figure 15) the lone particle spends most time at the lower levels. The exponential form of its average occupation of levels arises because each movement between adjacent levels multiplies W by the same factor. This factor is just r, since in a collection of particles , many will be found at any instant doing what one particle does frequently. Thus we have

$$r = \frac{\text{no. of particles at lower of two levels}}{\text{no. of particles at higher of two levels}} = W'/W$$

where W is the number of arrangements with a certain total energy and W' is the number of arrangement with one more quantum added.

It can now be made clear why the <u>logarithm</u> of r is used to define temperature. If we have, for one quantum added,

$$W' = W \times r$$

then $$\Delta \ln W = \ln r$$

and $$\Delta S = k \, \Delta \ln W = k \ln r$$

For two quanta added, ΔS is twice as large. If the energy U of the system is increased by dU, at constant volume, a number dU/ε quanta must be added. If dU is small, so that r does not alter too much,

$$dS = (dU/\varepsilon) \, k \ln r$$

and if we define

$$kT = \varepsilon / \ln r$$

then $$T = dU/dS$$

or $$dS = dU/T \qquad \text{(both at constant volume)}$$

Temperature is thus the ratio of the energy added to its effect on molecular arrangements. In an important sense, 1/T is more fundamental than T, being the rate of change of entropy with energy added. Thus near absolute zero, extra energy generates a very large increase in entropy, just as does adding a little salt to pure water. At high temperatures, adding or taking away energy alters the entropy only a little (just as adding salt to sea-water makes little difference). In this sense, a 'good' temperature scale would run from infinity (very cold and unattainable) to zero (very hot).

Flow of energy under a temperature difference, bringing about thermal equilibrium now looks like this. Given two systems, one hot and one cold,

$$r_{hot} < r_{cold}$$

$$\ln r_{hot} < \ln r_{cold}$$

$$T_{hot} = \varepsilon / \ln r_{hot} > \varepsilon / \ln r_{cold} = T_{cold}$$

When one quantum passes from hot to cold,

$$\Delta S_{hot} = -k \ln r_{hot}$$

$$\Delta S_{cold} = k \ln r_{cold}$$

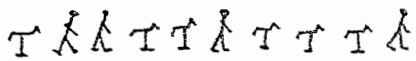
so that the entropy of the cold object increases by more than the entropy of the hot object decreases. The entropy of the two combined increases. It is just for this reason - the entropy increasing character of spontaneous energy flow under a temperature difference - that we distinguish **thermal flow of energy** (commonly called 'heat') from work, where no entropy change need take place.

From a fundamental point of view, the importance of the relation dS = energy change/T, is that we **no longer have to count!** Measurements with joulemeters and thermometers can be used to determine entropies, and so in a simple way to gain access to changes in W without having to work out a detailed molecular picture and count arrangements. Conversely, such measurements give insight into what may be going on at the molecular level. (See Section 9, LOOKING AT ENTROPIES).

7. THE EINSTEIN SOLID

In the discussion of Section 6, particles on equally spaced levels serve as a vehicle to discuss the nature of temperature and thermal equilibrium. The system has an interpretation, however, as a model of monatomic solids, first introduced by Einstein. The solid is modelled as a set of harmonic oscillators, loosely coupled so as to exchange energy without altering the levels available to any one particle. The level spacing ε is then $h\nu$, where ν is the classical oscillation frequency.

We are interested in the factor by which the number of arrangements W of oscillators on levels increases when one quantum is added. Imagine a procession of N herdsmen leading geese to the fields:



Each herdsman is an oscillator; the number of geese which follow him is the number of quanta it possesses (quantum number). W is the number of such processions with fixed N and n. Another goose can join the procession in N+n places (it cannot lead!). Thus where there are W possible processions, there are now (N+n)W. But this is too many, for these geese, being 'quanta', are all alike. No one can tell which of the n+1 geese is the new one, so W must be divided by n+1. Thus,

$$W'/W = (N + n)/(n + 1) \qquad \text{(adding one quantum)}$$

n being large, n+1 is almost equal to n, and

$$W'/W = 1 + N/n$$

Now n is the total energy U, divided by the quantum size ε, so

$$r = W'/W = 1 + N\varepsilon/U$$

The previous relation (Section 6) between temperature, r, and energy thus gives

$$kT = \varepsilon/\ln (1 + N\varepsilon/U)$$

Dulong and Petit knew that, at high temperatures, the molar thermal capacities of monatomic solids were very similar, and used this to determine molecular weight. This result follows at once if we take $n = U/\varepsilon$ much greater than N, so that

$$\ln (1 + N\varepsilon/U) \approx N\varepsilon/U$$

when $kT = \varepsilon/\ln (1 + N\varepsilon/U) \approx U/N$

Since particles can be oscillators in three independent dimensions, in one mole of particles there are N = 3L oscillators, and we obtain

$$T \approx U/3kL$$

giving a constant thermal capacity per mole of 3kL.

Einstein's use of the model did not make the approximation, expressing

$$kT = \varepsilon/\ln (1 + N\varepsilon/U)$$

in the form

$$U = N\varepsilon/\exp [(\varepsilon/kT) - 1]$$

and with N = 3L and $\varepsilon = h\nu$, we get the familiar solution for the internal energy of the Einstein solid. Thus we see how the naive arguments offered before relate to one of the important early results of quantum theory and statistical mechanics. The result is of minor important to chemists, however, and there is no reason to present it except for interest, and to offer teachers a wider perspective.

8. THE BOLTZMANN FACTOR

We have, almost without noticing, already obtained a result of central importance to chemists and phyisicists, namely the Boltzmann factor. We can re-write

$$kT = \varepsilon/\ln r$$

as $1/r = \exp (-\varepsilon/kT)$

interpreting 1/r as the ratio

$$1/r = \frac{\text{no. of particles in higher level}}{\text{no. of particles in lower level}}$$

where the levels differ by energy ε.

The previous argument also provides the underlying meaning of the Boltzmann factor. It is just the factor, less than unity, by which the number of arrangements W in a heat bath is multiplied when energy is borrowed from the heat bath. It thus gives the probability that such energy will be borrowed, by chance fluctuations.

Applications of the Boltzmann factor to activation processes are almost too numerous to mention, and many offer useful bridges between physics and chemistry. Thus one can argue that the vapour pressure of water may be given approximately by

$$p = \text{constant} \times \exp (\Delta H/LkT)$$

or that certain rates of reaction may be well modelled by

$$\text{rate} = \text{constant} \times \exp (-E_A/kT)$$

Somewhat more physical examples include defects in solids, diffusion in solids and liquids, viscosity in liquids and creep in solids.

Electrical examples include currents in semiconductors. In many such cases, useful simple experimental work is possible in school.

The strong dependence of the Boltzmann factor on temperature is striking, and has important effects on phenomena which depend on it. Thus an explosive may fairly safely be kept at a low temperature, where the rate is negligible, but be set off by heating a small part, which then reacts, heating the rest, so that the reaction runs away.

Numerical values, for example from a calculator, have value. The table below shows how two orders of magnitude variation in E/kT leads to more than forty orders of magnitude in the Boltzmann factor.

E/kT	exp(-E/kT)
1	0.37
2	0.135
5	0.007
10	$4.5\ 10^{-5}$
20	$2.1\ 10^{-9}$
50	$1.9\ 10^{-22}$
100	$3.7\ 10^{-44}$

The reason is intuitively clear from the previous computer shuffling game. A particle can get a large energy only by the chance arrival of many quanta without chance losses, and the likelihood of such a sequence, like that of throwing many heads in a row, is smaller the longer the sequence.

Numerical values for (e.g.) evaporation of water are worth inspection. H_{evap} = 40.6 kJ mol^{-1}, so the energy E per molecule is $6.8\ 10^{-20}$J, and with T = 300K, E/kT = 16.5 and exp(-E/kT) = $7\ 10^{-8}$. Water does evaporate at room temperature, but slowly. The smallness of the Boltzmann factor makes drying wet washing a significant problem, but it is not so small as to make it effectively impossible, as is waiting for rocks to evaporate!

As is well known, the Boltzmann factor can be obtained in other ways, notably by arguments about the exponential variation of density with height in an isothermal atmosphere, or (the same idea) from the classic Perrin experiment. It may be useful to compare these with the previous approach.

Perrin's idea was that tiny particles of matter - large on an atomic scale - suspended in a liquid might be made to reveal the nature of molecular motions. That such particles showed a continual random motion had been known for a long time - since Brown had observed the Brownian motion. What Perrin did was to investigate the energy of the motion.

Perrin used gamboge: a kind of latex. If layers of the suspension are looked at at different heights, by raising or lowering the microscope, there are seen to be fewer and fewer suspended particles at greater heights. Suppose a particle has radius 10^{-6} m, then its weight in water may be about $4\ 10^{-15}$N.

The particles do not sink, but are buffeted by moving water molecules. Suppose the molecules give a latex particle energy kT, say $4\ 10^{-21}$ J. This energy could lift it about 10^{-6}m, that is, by one diameter. An exceptional particle which got energy 10 kT could be lifted by about 10^{-5}m, or 0.01 mm.

We now want to know how many particles to expect at different heights. Let F be the sinking force on a particle, when F dh is the energy E needed to get a particle up dh in height. If there are n particles per unit volume, then in a volume of height dh, area A, the weight of the particles is F A n dh. The (osmotic) pressure difference dp across dh which supports this weight is given by

$$dp = - n F dh$$

But the latex particles behave like a gas at the water temperature T, with p = n k T, so that

$$dp = dn\ kT$$

where dn is the difference in n across dh. Since F dh = E, we have

$$dn/n = -E/kT$$

or

$$n = n_o \exp(-E/kT)$$

Another version of the same kind of argument concerns the equilibrium of an isothermal atmosphere under gravity, which we may call the 'exponential atmosphere' argument. It appears simpler still. The pressure difference across a horizontal layer must be enough to support the weight of that layer, giving at once an exponential decrease in density with height at a given temperature. However, it obscures, even more than does the Perrin experiment, the underlying mechanism. One can imagine Perrin's particles obtaining energy by chance from the water in which they are suspended, but from what do air molecules obtain the energy needed to rise in the gravitational field? The answer has to be that, to have such an atmosphere at the same temperature at all heights, some 'heat-bath' extending up into the atmosphere would be needed - an imaginary tall copper tower, for example. The absence of the very source of the Boltzmann factor from the argument may be considered a significant price to pay for its simplicity.

9 LOOKING AT ENTROPIES

Being now able to "count" changes in numbers of arrangements of a heat bath, with a joule meter and a thermometer, the way is open to determine entropy changes and (if suitable zeroes are defined) entropies of substances. It is useful to become accustomed to the values obtained, and to see that patterns amongst such values can make sense.

Standard entropies below are Third Law entropies.

Evaporation

There is a large increase in volume on evaporation, so from the general argument of Section 4 we expect a considerable entropy change. The volume change may be of the order 1000:1 so extrapolating boldly and using

$$\Delta S = Nk \ln V_2/V_1$$

we estimate for this effect $\Delta S = Nk \ln 1000 \approx 60$ $JK^{-1}mol^{-1}$. Such an estimate does not include any entropy increase from the destruction of a degree of order in the liquid state, so we expect actual values to be larger. Trouton noticed that, calculating the entropy change from

$$S = H_{evaporation}/T_{boiling\ point}$$

the entropy changes on evaporation of many liquids were rather similar. The table shows how Trouton's rule works out.

Substance	Formula	H/kJ mol^{-1}	T/K	S/$JK^{-1}mol^{-1}$
carbon disulphide	CS_2	27.2	319	85.3
trichloromethane	$CHCl_3$	29.3	334	87.7
tetrachloromethane	CCl_4	30.4	350	86.8
benzene	C_6H_6	30.9	353	87.5
methanol	CH_3OH	35.2	338	104.1
ethanol	C_2H_5OH	38.5	352	109.4
hexane	C_6H_{14}	28.8	342	84.2
octane	C_8H_{18}	34.9	399	87.5
methylbenzene	C_7H_8	33.4	384	87.0
cyclohexane	C_6H_{12}	30.1	354	85.0
methylcyclohexane	C_7H_{14}	31.7	374	84.8
water	H_2O	40.6	373	108.8
sulphuric acid	H_2SO_4	50.2	599	83.8
mercury	Hg	56.8	629	90.3

Many of these liquids have ΔS_{evap} of the order 80 - 90 $JK^{-1}mol^{-1}$. The exceptions in the table have hydroxyl groups and form hydrogen bonds in the liquid, giving it more structure. This raises the entropy of evaporation.

The entropy of evaporation is some 20 $JK^{-1}mol^{-1}$ greater than the previous guess using only the volume increase and is larger still for water. It is of interest to compare entropies of melting. For water, the entropy change $\Delta H/T$ (melting) is 22 $JK^{-1}mol^{-1}$ (6000 $Jmol^{-1}/273K$), suggesting that the loss of structure in going from solid to liquid is similar to, but rather less than, the loss from liquid to gas.

Liquid water is, in fact, a rather well-structured substance and this accounts for many of the properties (notably the high melting and boiling points) which make it part of the basis of life, and which make the chemistry of aqueous solutions complicated and interesting.

Similarity and dissimilarity

Compare the following values:

	S^θ/J K^{-1} mol^{-1}		S^θ/J K^{-1} mol^{-1}
cobalt	30.0	diamond	2.5
nickel	29.9	lead	65.0

Cobalt and nickel are extremely similar in atomic mass, crystal structure, and bonding in the solid, and have almost identical molar entropies.

Diamond and lead, however, contrast sharply. The arguments of section 6 suggest why. Diamond has atoms of small mass, with stiff bonds between them, so the oscillation frequency is large. From $\varepsilon = h\nu$, the "size" of energy quanta is large, so for a given energy, there are relatively few of them. Fewer quanta can be shared in fewer ways, so W is small and so is the entropy k ln W. Lead is the opposite: massive atoms, low frequency of oscillation and thus many "small" quanta, having many ways to be shared and thus a higher entropy.

Water of crystallisation

Compare:

	S^θ/J K^{-1} mol^{-1}	
Na_2SO_4 10 H_2O	592	
Na_2SO_4	149	
difference	443	(44.3 per mole H_2O)

The molar entropy of ice at 273K, 1 atm happens to be about 41 $JK^{-1}mol^{-1}$, and is rather comparable with the entropy one might attribute to each mole of H_2O in the hydrated crystal. (Note that the entropies for the salt are for 298K, so one expects a slightly higher value).

Complexity

Entropy increases with molecular complexity:

	S^θ/J K^{-1} mol^{-1}
benzene C_6H_6	125
hexane C_6H_{14}	296

The compact benzene ring has less entropy than the long floppy hexane chain, which can move and bend in more ways, leading to a larger number of molecular arrangements. To make such comparisons, however, account must be taken of masses since more massive molecules tend to have large entropies.

Consider:

	$S^{\ominus}/J\ K^{-1}\ mol^{-1}$
H_2	131
He	126
Ne	146
Ar	155
Kr	164
Xe	170
Ra	176

A plot of $S^{\ominus}$ against ln m is linear (slope 3/2 kL) for the noble gases, but the diatomic molecule H_2 does not fit. Lighter than He, it has greater entropy, because it is more complex.

Note also some relative magnitudes. Entropies of monatomic gases exceed 100 $JK^{-1}mol^{-1}$, essentially because of their large volume. In the liquid or solid state, one may need molecules with more than half a dozen component particles to attain a comparable entropy (cf Na_2SO_4 or benzene). Entropies of simpler solids with modest atomic mass (e.g. cobalt, nickel) are typically well below 100 $JK^{-1}mol^{-1}$ but rarely below 10 $JK^{-1}mol^{-1}$.

Strictly speaking, this section relies on ideas about equilibrium in later sections, because entropy changes within a material are found by measuring entropy changes in a heat bath, and equating their magnitudes for the special equilibrium case:

$$\Delta S_{object} + \Delta S_{surroundings} = 0$$

10. HOW TO MAKE REACTIONS GO THE WAY YOU WANT

I may want water to evaporate to dry the washing or to make salt from sea-water, or I may want to condense it from the vapour in a desalination plant or in distillation. I may want to make alcohol from carbon dioxide and water or I may want to burn alcohol in a lamp, an engine, or as part of getting a little drunk. I may want to extract magnesium from its ore, or to make magnesium oxide in a photographic flash-bulb. I may want to make ammonia for fertilisers from hydrogen and nitrogen, or to break it down for analysis. I may want to dissolve a salt, or to crystallise it from solution. I may make a byproduct in an industrial process, and then want to recover its constituent elements (e.g. sulphur in making soda).

In all such cases, we want to know how to make, or encourage, a reaction to go in one direction or the other. The answer to both questions is the same: arrange that the entropy increases. At one level, the answer is trivial: to say that the entropy increases is to say that W increases, which is to say, in different words, that the reaction will happen - even though by chance - in the desired direction. At another level, the answer is entirely non-trivial: we have to find the circumstances under which the entropy will increase. For that, we need to be able to understand and predict entropy changes.

We can piece together some qualitative advice, to begin with. Since the entropy of a gas increases with volume (decreases with pressure), in a reaction with gaseous products one should have the partial pressure of products low. Washing dries best in a dry atmosphere. Further, if a reaction increases the number of particles, the entropy again increases, so that on this score (not yet thinking about other factors), we expect the forward reaction of

$$N_2O_4 \rightleftharpoons 2NO_2$$

to be less of a problem than the reverse reaction. In the case of

$$N_2 + 3H_2 \rightleftharpoons 2NH_3$$

we do want the ammonia as product and the source of entropy change presently under consideration is not in our favour (the direction we want reduces the number of particles). Perhaps a low pressure of NH_3 might help.

Entropy changes arising from exchange of energy with the surroundings are also important, sometimes dominant. Thus

$$2H_{2\,(g)} + O_{2\,(g)} \rightleftharpoons 2H_2O_{(l)} \qquad \Delta H^{\ominus} = -286\ kJ\ mol^{-1}$$

goes spontaneously (explosively) to the right (if set off) despite the reduction in volume and number of particles, because of the large entropy increase when the energy produced is spread in surroundings at 300 K. But we know also that this entropy change depends on the temperature being less the higher the temperature. Thus for a reaction to go in the exothermic direction, it may help to keep the reaction cool. Thus

$$2H \rightleftharpoons H_2$$

is strongly exothermic, and on the cool surface of the Earth essentially all gaseous hydrogen is molecular. But on the Sun, the entropy increase from the same energy given to the surroundings is less, and the entropy increase from doubling the number of particles may win, so that hydrogen will be mainly dissociated.

Endothermic reaction directions thus tend to be favoured by hot surroundings. The melting of ice cubes is a simple case in point, as is the evaporation of water. Energy is taken from the surroundings, but if these are hot, the entropy decrease is reduced, thus assisting that direction to have a net entropy increase.

Water melting or freezing illustrates the point. We have:

	$S_{273,\ 1\ atm}/J\ K^{-1}\ mol^{-1}$
$H_2O_{(l)}$	63
$H_2O_{(s)}$	41
ΔS	22

If 1 mole of H_2O freezes, there is an entropy decrease amounting to 22 JK^{-1}, but also an entropy increase of the surroundings of 6000/T JK^{-1}. If T happends to be 250K, the net entropy change is

$$-22 + 6000/250 = -22 + 24 = +2$$

so that the entropy change of the surroundings wins and the water freezes. At 300 K, for the reverse direction, in which ice melts:

$$+22 - 6000/300 = +22 - 20 = +2$$

and the entropy change of the H_2O wins, and the ice does melt. Thus water freezes and ice melts under the same general condition: an increase of entropy. We can influence which happens by controlling the circumstances, here the temperature of the surroundings.

Clearly there is some temperature (we know it to be 273 K) at which the net entropy change is zero – that is

$$6000/T = 22$$

$$T = 273$$

Here we have calculated, for this primitive case, a condition for equilibrium. Other calculations for chemical reactions are more complicated, but the underlying idea is the same.

11. FREE ENERGY

Since Gibbs, chemists have another useful way of looking at the direction of change. Suppose we freeze one mole of water. The entropy of the water decreases, $\Delta S(H_2O) = -22\ JK^{-1}\ mol^{-1}$. Suppose the surroundings are at 250 K. How much energy must be passed to the surroundings for the reaction not to produce a net entropy decrease, that is, to begin to be possible?

The answer must be that we must balance the decrease if 22 JK^{-1} by a corresponding increase. Thus the energy required is $-T\ \Delta\ S(H_2O)$, or

$$250 \times 22 = 5500\ J\ mol^{-1}$$

In fact, however, the melting produces more than is needed, namely 6000 J mol^{-1}. The difference, 500 J mol^{-1}, is what chemists call the free energy ΔG. In this case it is energy we did, but need not have, passed to the surroundings. If we were clever enough, we could still freeze water in a freezer at 250 K, and use some or all of that 500 J mol^{-1} for other purposes.

We notice that the free energy is just

$$\Delta G = -T_{surroundings}\ \Delta\ S_{total} = -250 \times 2$$

Also since

$$\Delta S_{total} = \Delta S(H_2O) - \Delta H(H_2O)/T_{surroundings}$$

we have

$$\Delta G = -T\Delta S(H_2O) + \Delta H(H_2O)/T_{surroundings}$$

Teachers will notice that this line of argument runs counter to a common, but quite misleading way of presenting free energy. Frequently, free energy is discussed as a competition between entropy change and minimising potential energy, as if there were two influences on the direction of change, and not just one. Potential energy, such as that of a ball rolling on a curved track, tends to a minimum because this increases the entropy, here by warming the ball and track. In the absence of friction or other dissipative forces, the potential energy does not tend to a minimum (in fact, such a ball spends least time at the bottom!).

Most fundamentally, $G = -T\Delta S_{total}$, under conditions of constant pressure. Under other conditions, $-T\Delta S_{total}$ has a different value, and is the appropriate free energy. Thus this formulation embraces all free energy functions. That is, if a reaction produces a net entropy increase, we could always in principle search for a way to extract energy equal to the free energy and use it for other purposes. We cannot have more, since that would make the net entropy change negative.

Chemists may like to see how the same formulation works for discussing the efficiency of engines. If a furnace at temperatures T_{hot} exchanges energy q thermally with a cooling tower at temperature T_{cool} the net entropy change is

$$-q/T_{hot} + q/T_{cool}$$

Using a power station just to warm the countryside produces a net entropy change

$$\Delta S_{total} = q\ [\ (1/T_{cool}) - (1/T_{hot})\ ]$$

However, there is no need to pass all the energy q out at the cooling tower, since only just enough to make the net entropy change non-negative is required. The work w we can have is indeed the free energy in this case:

$$w = -T_{cool}\Delta S_{total} = -q\ [\ 1 - (T_{cool}/T_{hot})]$$

and we arrive immediately (in the chemical sign convention) at the usual expression for the maximum efficiency.

Life itself depends on the same device. Photons from a hot sun arrive at the Earth and are absorbed and re-radiated at a lower temperature (one may also imagine "big" photons splitting into many "smaller" ones) thus generating a continual increase of entropy. Plants exploit this supply of free energy (entropy increase) to make possible reactions such as making sugars from carbon dioxide and water. Life is possible because of the strong disequilibrium produced by being near a star. Indeed, living may be seen as 'feeding' on free energy, that is, on 'negative entropy'.

12. GASEOUS EQUILIBRIA

We now look in some detail at equilibrium, to show how equilibrium constants arise from entropy considerations. Consider the Haber reaction:

$$N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)} \qquad -92 \text{ kJ mol}^{-1}$$

Qualitatively, we expect the direction in which NH_3 is the product to be favoured by the energy given to the surroundings, but to be disfavoured by the reduction in the number of particles. To manipulate the reaction, one can control the temperature and the partial pressures of reactants and products. Lowering the temperature will make the increase of entropy due to energy going to the surroundings yet bigger, which may help, but may also slow the reaction drastically.

The relevant data is:

	$S^\theta/JK^{-1}mol^{-1}$
N_2	191.4
H_2	130.6
NH_3	192.5

Imagine "passing" one mole of (say) N_2 through the reaction. (If preferred, pass a small amount dm mole and multiply all succeeding values by dm). First draw up an entropy balance sheet in the standard state:

Standard state entropy balance sheet

Event	Entropy change at standard state
Lose 1 mole N_2	-1 (191.4)
Lose 3 mole H_2	-3 (130.6)
Gain 2 mole NH_3	+2 (192.5)
$\Delta S^\theta_{chemicals}$	-198.2
$\Delta S_{surr} = 92\ 10^3/298$	+308.7
ΔS_{total}	+110.5

We conclude that in the standard state the reaction can proceed in the desired direction. We now consider the entropy balance sheet at pressures other than the standard pressure. We know that

$$S = S^\theta - Nk \ln p/p^\theta$$

and we know why: at lower pressures the molecules have more room and can be arranged in more ways. Thus we draw up a modified balance sheet, with a new column for corrections to the standard entropies.

Balance sheet for non-standard pressures.

Event	Entropy change in standard state	Corrections for non-standard pressure
Lose 1 mole N_2	-1(191.4)	$-1(-Lk \ln P_{N_2}/P^\theta)$
Lose 3 mole H_2	-3(130.6)	$-3(-Lk \ln P_{H_2}/P^\theta)$
Gain 2 mole NH_3	+2(192.5)	$+2(-Lk \ln P_{NH_3}/P^\theta)$
$\Delta S^\theta_{chemicals}$	-198.2	
ΔS_{surr}	+308.7	
ΔS_{total}	+110.5	$-Lk [-1 \ln P_{N_2}/P^\theta - 3 \ln P_{H_2}/P^\theta + 2 \ln P_{NH_3}/P^\theta]$

At equilibrium we have $\Delta S_{total} = 0$. The term on the right contains a constant ($-2Lk \ln P^\theta$), which we can evaluate, or make vanish by working in units of atmospheres, for which $P^\theta = 1$. Taking the latter option, for ΔS_{total} to be zero we have

$$Lk [-\ln P_{N_2} - 3 \ln P_{H_2} + 2 \ln P_{NH_3}] = 110.5$$

or $$\ln \left[\frac{P^2_{NH_3}}{P_{N_2} P^3_{H_2}} \right] = 110.5/Lk = 13.3$$

which can be written

$$K_p = \exp(13.3) = 6\ 10^5$$

The most essential point is that K_p arises from this argument because changing the partial pressure (i.e. concentration) of the reactants or products alters the entropy change. The expression which gives K_p is nothing more than the basic equation for equilibrium

$$\Delta S_{total} = 0$$

and the terms containing the pressures are just contributions to the total entropy change.

Further, in this calculation, the value 110.5 equated to $Lk \ln K_p$ was just the net entropy change in the standard state. Thus

$$Lk \ln K_p = \Delta S^\theta_{total}$$

which is just to say that partial pressures can adjust so that at equilibrium away from the standard state, their entropy contributions cancel the net entropy change in the standard state.

But (Section 11) $-T\Delta S_{total}$ is just the free energy, so

$$\ln K_p = -\Delta G^\theta/LkT$$

which is the form most familiar to chemists. Clearly this result can be obtained by shorter arguments, but the virtue of the preceeding discussion is to show how and why it works, and to bring out that it is just a re-writing of $\Delta S_{total} = 0$.

13 EQUILIBRIUM AND CONCENTRATION

Many reactions occur in solution and the concentrations of species in solution have important effects on entropy changes. The idea is simple enough: adding a little salt to pure water increases the entropy because many ways of interchanging unlike particles then exist. Diffusion equalises concentrations because in that way the entropy increases (compare thermal flow of energy from hot to cold). In the previous section we saw how partial pressures of reactants in gas reactions altered entropy changes, and so affected equilibrium. Now we construct a similar argument for concentrations.

When particles diffuse from high to low concentration, there is an entropy increase, which is to say that a difference in concentration has free energy. Our nerve cells produce concentration differences by chemically pumping Na^+ ions into the cell and K^+ out, and then use the difference to generate electrical potential differences, the means by which the brain signals to the fingers. The effect is easy to show with beakers of copper sulphate solution, one dark and one light blue, with a digital millivoltmeter connected to copper electrodes and a salt bridge between the beakers. Cu^{2+} ions come out of solution from the more concentrated solution, making that electrode positive, and go into solution on the more dilute side, making that negative. Electrons flow between the electrodes, and can do work.

To discuss concentration effects on equilibrium, we need to know by how much the entropy of a given amount of a certain species in solution changes when the solution is made more or less dilute. The approximate answer is the same in form to that given before for the expansion of a gas. Figure 16 shows a certain concentration of solute particles, about to be halved by doubling the amount of solvent.

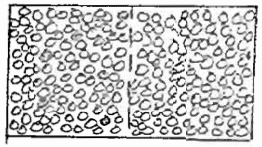


Figure 16 Doubling the dilution of a solution.

Each solute particle can now change places with twice as many solvent particles. If there were W ways of changing places before the dilution, there will be

$$W' = W \; 2^N$$

ways after, where N is the number of solute particles. Thus, as in Section 4,

$$\Delta S = k \, N \ln 2$$

and for 1 mole of solute particles, $\Delta S = 6 \text{ J K}^{-1}$. The number 2 is

now the ratio of two concentrations, and the general form of the entropy change is

$$\Delta S = -k \, N \ln (\text{concn. after}/\text{ concn. before})$$

(The minus sign says that concentration going down puts entropy up.) If entropies are referred to a standard concentration, then

$$S = S^{\ominus} - k \, L \ln [\, X \,]/[\, X \,]^{\ominus}$$

for a species X, S being the molar entropy. Note that this entropy calculation does not include an entropy of the solvent itself, but only the effect of its presence on the entropy of the solute.

These results can not be relied on to the same extent as the similar ones for gases. Solutions are complex, and the naive assumption that any particle is equally likely to change places with any other is not generally valid. For this reason concentrations are replaced in the calculation by emprically determined activities. Even so, the argument is qualitatively a good guide to why entropy changes with dilution, and departures from the results it gives help to give information about the nature of the solution.

We can now estimate what size of electrical signal a nerve cell can produce. Chemical transport maintains a concentration ratio of about 10:1 between inside and outside of the cell. If (say) Na^+ ions pass across this difference, there is an entropy increase. But this process can happen as long as there is not an entropy decrease, so it is possible for energy to be taken from the cell surroundings, and to be delivered as electrical work w. The largest possible value of w is given by,

$$-w/T_{surr} + \Delta S_{concn.\ diff.} = 0$$

But (for a singly charged ion) $w = N \, e \, E$, where E is the emf, and N and e respectively the number of ions moving and their charge. Thus for a 10:1 concentration ratio,

$$-N \, e \, E/T + k \, N \ln 10 = 0$$

$$E = T \, (k/e) \ln 10 = 60 \text{ mV at } 300 \text{ K}.$$

The same reasoning suggests about 30 mV for two copper sulphate solutions (charge 2e on an ion), for the same concentration ratio. This calculation takes no account of any enthalpy change on dilution, and this is in fact a significant factor for copper sulphate, so that the emf's from pairs of solutions in the same concentration ratio are not the same.

The equilibrium of a redox reaction can be thought about in the same way as we considered that of gas reactions. Consider the entropy balance sheet for passing 2 moles of electrons through the reaction,

$$Cu + 2Ag^+ \rightleftharpoons Cu^{2+} + 2Ag \qquad +\Delta H$$

In the standard state we have:

event	entropy change
lose 1 mole Cu	$-S^{\theta}(Cu)$
lose 2 mole Ag^{+}	$-2S^{\theta}(Ag^{+})$
gain 1 mole Cu^{2+}	$+S^{\theta}(Cu^{2+})$
gain 2 mole Ag	$+2S^{\theta}(Ag)$
above adds to	$\Delta S^{\theta}_{\text{chemicals}}$
+ surroundings	$-\Delta H^{\theta}/T$

total entropy change $\Delta S^{\theta}_{\text{chemicals}} - \Delta H^{\theta}/T = -\Delta G^{\theta}/T$

If the concentrations of ions in solution now differ from the standard state, the balance sheet changes:

event	entropy change	corrections
lose 1 mole Cu	$-S^{\theta}(Cu)$	
lose 2 mole Ag^{+}	$-2S^{\theta}(Ag^{+})$	$-2(-kL \ln[Ag^{+}]$
gain 1 mole Cu^{2+}	$+S^{\theta}(Cu^{2+})$	$+(-kL \ln[Cu^{2+}]$
gain 2 mole Ag	$+2S^{\theta}(Ag)$	
above adds to	$\Delta S^{\theta}_{\text{chemicals}}$	
+ surroundings	$-\Delta H^{\theta}/T$	
total entropy change	$-\Delta G^{\theta}/T - kL \ln [Cu^{2+}]/[Ag^{+}]^{2}$	

Setting the total entropy change to zero for equilibrium we get

$$\ln K_c = \ln [Cu^{2+}]/[Ag^{+}]^{2} = -\Delta G^{\theta}/kLT$$

Remembering that the free energy relates directly to the cell emf, as previously, the effect of change of concentration on emf follows at once.

REAL SYSTEMS ON THE ONEWAY ROAD TOWARDS DISORDER

(What you always wanted to know about entropy and never dared to ask II)

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1. Concepts of disorder

What is disorder? Children very often disagree with their teachers or parents when answering this question. Their "personal" order is in many cases a very specific but mostly irregular arrangement of their belongings like toys or books, an arrangement which has an individual meaning for themselves but for nobody else. A physical approach to the concept of order and disorder should be independent of taste, i.e. personal meaning, relying only on a kind of general meaning, which we like to call structure. This does not at all mean that individuality is considered an unphysical concept - on the contrary, the statistical approach to thermal physics is based on the assumption of complete individuality of single particle motion in a large ensemble - it is more or less a question of standpoint: We deliberately concentrate on the average behaviour of a big system and do not care for fluctuations, i.e. deviations from this average. (which are small for macroscopic systems, but nevertheless responsible for some "every day" phenomena like e.g. the blue sky). In this respect, the view of a statistical physicist is comparable to that of an industrial manager or a politician who always have to consider large groups of individuals without strong collective behaviour. Statistical physics is therefore not more inhuman than ecomomics or politics on the large scale.

To find out the amount of "general" disorder in a "specifically ordered", single situation, we choose the strategy of information theory and consider the "general" disorder of a certain class of "specifically ordered" situations as the average amount of information we need to find out a certain specific element in the large set of total possibilities. As quantitative measure for this information we use the minimal number of Hamlet type questions (yes or no,

to be or not to be) that must be answered in order to fix with certainty a single element in the large vessel of possibilities. This quantitative measure of disorder, the so called number of "bits", has the advantage of being obviously additive for two different, independent systems. It is also frequently used as a measure of "hidden" information in nonphysical applications like TV question games etc., where it is usually restricted to a number smaller than ~ 10 corresponding to $2^{10} \approx 10^3$ total possibilities.

2. Desk type and disco type disorder in phase space

The set of total possibilities in physics is called phase space and consists of all possible pairs of position and momentum values. Every such pair is a complete classical description of a "pure" state of a system of point particles. As the total number of points in phase space is infinite, even uncountable, we must choose an (arbitrary) cell structure to define, on the classical level, "fuzzy" microstates which always remain finite in total number if e.g. the total energy and particle number of a system are kept fixed. Quantum mechanics makes this lattice description essentially unique; in the phase space formulation, the volume of a single phase cell must be something like h^{3N}, where N is the total number of particles. As we are more interested in practical applications of the entropy concept in the real world than in a sophisticated theoretical foundation of statistical mechanics, we can forget about quantum cells: In all practical examples we consider, it is only the entropy difference between two competing classes of configurations in phase space which really enters the problem. We therefore use the natural cell structure which is given by one of the competing classes of configurations as a reference to determine the necessary number of Hamlet-type questions for making "precise" a special configuration of the other class. "Precise" refers here to the given cell structure and the corresponding numbers of bits is proportional to the entropy difference between the two classes of phase space configurations. As we have seen in the first part of this contribution, the relevant factor equals $0.7k$, where 0.7 stands approximately for the natural logarithm of two and k is the Boltzmann constant.

2.1 The desk type disorder

Although the physical concept of phase space is very abstract and far away from direct imagination, certain projections of it down to three (or two) dimensions have a very intuitive, pictorial meaning. Everybody who is used to work at a desk, knows that the configurational chaos of all the objects on its surface always increases with time and the original order is never restored "by itself". As we have stressed already, this "desk type disorder" does not consist in a special, irregular arrangement of objects, but in the partial loss of knowledge about their actual positions. It is a "cold" disorder; that means, it does not involve any motion (although motion is necessary for every transition to another state). The applications to everyday physical situations, which we treat in the sequel, shall make clear in which sense a single spatial arrangement of points - representing e.g. a microscopic "flashlight" photograph of a many-particle-system - may characterise quantitatively the amount of desk-type disorder relative to a given reference situation. But although this kind of chaos in spatial configuration is a very intuitive concept, it is not sufficient for a complete description of thermodynamic processes, not even under isothermal conditions where one could think the chaos in momentum space to stay constant. The reversibility of phase transitions like evaporation, melting or solution, which all occur at constant temperature, contradicts any principle of "maximal desk type disorder", because the "backward" processes like condensation, solidification and crystallisation obviously decrease the configurational disorder in coordinate space. Therefore it is necessary to consider as well

2.2 The disco type disorder

A croweded disco is a model for a many particle system with low desk type disorder, because it is nearly in a state of closest spatial packing; in this case, there exists only one single spatial arrangement which is compatible with the boundary conditions (= the walls of the room) if we treat the dancers as indistinguishable. (In our "classical" model, the latter is a consequence of the low average number of disco photons) but on the other hand, there is a lot of disorder in the state of motion of the dancers, because their movements are intense and practically uncorrelated (in spite of the great musical "pumping power", the threshold for a laser-like collective behaviour is usually not

reached and even the pair correlations are often very weak). In contrast to the intuitive concept of desk disorder, disco disorder is not so easily understandable, because we need, for an adequate representation, some kind of movement (film, computer simulation, ant hill etc.) and cannot rely on static pictures.

The quantification of disco disorder, (which turns out to be absolutely necessary for every practical application, as we shall see in the sequel) can again be restricted, in all situations considered, to an expression for differences of disorder in momentum space between two different states of a system. Nevertheless, we have not found an easy and explicit way to explain the fact, that - independent of the energy spectrum! - the change of disco type disorder in a system equals E/0.7 kT bits, where E is the energy transfer to or from the "individual" disco type modes (in contrast to collective modes like center of mass motion, or standing waves). The real problem in this connection seems to be the "natural" quantification of the (phenomenologically introduced) concept of temperature.

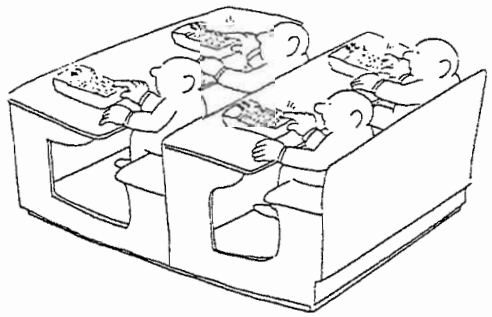
2.3 How trivial is the second law ?

While teachers have great difficulties in understanding-and therefore also in teaching-the Second Law because they usually have been trained in Newtonian Mechanics before meeting Thermodynamics,children usually consider it as simpler and more natural than many other principles of physics.They have all made the personal experience that material objects get broken after a certain while and that every process going back and forth finally comes to a dead end(swings, car batteries,phototropic sunglasses etc.).Should we therefore learn the Second Law from our children who seem to be more familiar with the concept of disorder and decay? If Thermodynamics would be nothing else then the depressing story about material breakdown, a theory about individuality lost by the sucessive leveling up of all macroscopic features, in short the description of a pilgrimage along a oneway road towards the ultimate equilibrium state called death, then we should ban it from our teaching at school.But Thermodynamics has also another,complementary face reflecting the joy of life and presenting a surprise:

- The sky,unlike crumbling buildings,doesn't fall down,but stays in the blue height up to some 10 km.
- A temperature difference eg. between air and skin,can increase instead of decreasing by the only help of the thin water film we produce by transpiration.

- In the sky, clouds and snowflakes show the emergence of structure and order out of chaos and equipartition.
- The evolution of life i.e our local arrow of time leads from the primordial atmosphere (a chaotic equilibrium state with maximal entropy) to the wonderful and fascinating complexity of living matter.The invention of consciousness and,finally,self-reflection creates a new kind of free and independent individual with completely new types of communication like Hamlet, Don Giovanni or the Venus of Milos .

It is the spirit of these -merely open- questions which should animate our difficult, but challenging task of teaching the living face of Thermodynamics and Statistical Physics to the living faces of our children.



3. The oneway road towards disorder

There is a physical folklore saying that systems have a tendency to approach a configuration of minimal energy. It is often illustrated by stones falling downhill or pendulums reaching the lowest point. Is energy therefore a road sign to equilibrium? For a closed system, total energy is of course conserved, so it cannot serve as a measure for "distance to equilibrium" (or, in the slang of physics, a Ljapunow function). If we consider the configurational energy alone (in the hope that it will enable us to make predictions about configurational chaos or, as we call it, desk type disorder) we find that for systems with single collective motion in bound states (as falling stones or oscillating pendulums), there is, on the opposite, a principle of maximal configurational (= potential) energy, if we look at the system randomly in time. Imagine, e.g. a ceiling lamp oscillating in a dark room: we will find it with greater probability at the highest points, when we switch the light on, because it is slower there and consequently spends more time at the points of high configurational energy. But if we wait sufficiently long, then we will find the lamp with certainty at the lowest point. But as there is finally only one configuration, then the desk type disorder of the state has decreased! (Although this argument seems convincing, we have cheated a little bit, because the concept of desk and disco disorder applies only to systems with many particles respectively degrees of freedom). What about the disco type disorder? The total energy E of the single mode of lamp oscillation has gone to the individual degrees of freedom of the surroundings (air and support) where it has increased the disco disorder by E/0.7 kT bit (k = Boltzmanns constant, T = absolute temperature). The principle we can see behind this behaviour is the increase of total disorder: If we convert an amount of potential energy E into kinetic one, it can be transferred by molecular motion to the surroundings (with temperature T) and increase there the disco disorder. But when the forces are attractive at large distances (which is the case in all physical systems having bound states), the release of potential energy, while increasing the disco disorder of the surroundings, decreases the desk disorder in the system itself! In order to find out the oneway road where the total disorder is enlarged by the greatest amount, we have to define desk and disco disordered not only qualitatively, but quantitatively, because they tend usually in opposite directions! (If this where not so, we presumably would not be here!).

In this competitive tendency we can see a chance for a phenomenon like "dissipative order": The best possible way of increasing total disorder in systems with attractives forces and bound states as they occur in chemistry or molecular physics may well be a transition to a highly structured bound state decreasing the desk type disorder, because the energy thus released increases the disco type disorder in the surroundings by an even greater amount, (if these surroundings are not to hot!) Life may be seen in this context as an effective procedure of waisting energy by transforming potential metabolic energy into kinetic one which then increases the disco disorder of the environment. So life may not only be well compatible with the second law, but possibly a consequence of it: The deep structure of creation really seems to be decay (P. Atkins).

3.1 Why Doesn't the Sky Fall on Our Head?

Although this question (which seems to be a nightmare of the gallic chief Majestix) doesn't represent a serious problem for many people at a first glance, it nevertheless contradicts a naive principle of "minimal configurational energy": If the air would behave like the penculum considered above, it would cover the earth's surface with a "liquid" layer which has a height in the range of 10 m, because the weight of an atmospheric air column is known to be balanced by a "water tower" (sometimes called "torre Celli") with a vertical extension in the above mentioned order of magnitude.(We neglect the difference in molecular mass between air and H_2O.)

As the diameter of a hydrogen balloon capable of carrying a man is roughly 10 m and therefore ten times greater than a floating water ball which supports a person standing on it, the density ratio between water (which is typical for all condensed phases) and air (typical for gases under normal, i.e. atmospheric conditions) lies in the range of 10^3. Therefore the "effective" or "scale" height of the atmosphere is 10 km, leaving enough space for birds and planes, but kept well inside the earth's gravitational field, which has an "effective" range of several thousand kilometers. Indeed this "typical" height of 10 km represents the state of

maximal total atmospheric disorder at a given temperature of 300 K on the earth's surface which is determined by the radiation equilibrium with the sun. (The "direct" solar heating of the atmosphere is weak because of its low density and "sharp" absorption lines in the thermally distributed radiation power spectrum.) If we double the height of the "condensed layer" with thickness $h_o \sim 10$ m, its desk disorder increases by one bit per particle, because we need one Hamlet-type question to get the information whether the particle is afterwards in the "upper" or in the "lower" floor. (From this argument it is also obvious that any further doubling of height again yields the same increase in desk disorder, namely 1 bit per molecule.) But raising the molecules against the earth's gravity costs a mean energy of $\sim mgh_o(2^n-1)/2$ where m is the (average) molecular mass of air, g the gravitational acceleration and n the number of times we double the initial "condensed" heigt h_o. As total energy is conserved, this n-fold doubling of height "cools" the earth's surface by extraction of an equal amount of thermal energy, which leads to a reduction of disco disorder on the surface by $mgh_o(2^n-1)/1.4\ kT$ bits/particle. (Particle means here: molecule of air, because these particles (with total number N) have to be lifted energetically by $E_{tot} = N \cdot mgh_o(2^n-1)/2$, causing a change in disco disorder of $E_{tot}/0.7\ kT$ bits in the surroundings, i.e. the earth's surface. It is important to note that this change is independent of the particle number in the surroundings, which permits to consider the limiting case of an infinitely extended "heat bath" with constant temperature in spite of finite energy exchange with the system considered, i.e. the atmosphere.) Thus the transition from n-fold to n+1-fold doubling of the initial height h_o changes the total disorder by

$$1 - \frac{mgh_o}{1.4\ kT}(2^{n+1} - 2^n) = 1 - \frac{mgh_o 2^n}{1.4\ kT} = 1 - \frac{mgh_n}{1.4\ kT} \text{ bits/molecule of air}$$

where $h_n = h_o 2^n$ is the actual height after the n-th step of doubling. As long as the above quantity is positive, the transition from h_n to $h_{n+1} = 2h_n$ occurs "spontaneously", because it increases the total disorder of the combined and closed system atmosphere + earth's surface. Thus we get - in our crude approximation of uniform particle distribution in all

"floors" - an equilibrium height $\bar{h} = 2 \cdot \frac{1.4\ kT}{mg} \approx 10$ km corresponding to $\bar{n} = 10$. Although our picture does not yield a decrease of density with height (which we can get by a more sophisticated maximization of total disorder), it leads immediately to an understanding of the nonuniform temperature distribution in the atmosphere, which is not described by the barometric formula: Because of the low thermal conductivity of air, the energy for molecular "lifting" cannot be supplied from the earth's surface alone: As the equilibrium height ~ 10 km corresponds to a ~ 10-fold doubling of the "condensed" height ~ 10 m, the last steps of this height doubling sequence cool the atmosphere itself and not the earth's surface. This means that in a height of 10 km, the (absolute) temperature is reduced by an amount in the range of its original value 300 K. Linear extrapolation thus leads to the correct range of vertical temperature gradient, namely 10^{-2} K/m, explaining the existence of glaciers ($T \lesssim 270$ K $\hat{=}$ 0° C) in a height of ~ 3 km.

3.2 Molecular Individualism and Evaporation: A Steam-Powered Struggle for Freedom

The name "gas" which has been invented by the flemish chemist van Helmont in the 16th century, stems from the Greek word "chaos" and is a very good description of the corresponding molecular situation, which has maximal desk disorder under the given conditions of temperature and pressure. Should not be all matter in this state? As the forces between neutral molecules are always attractive at large distances - a consequence of electrostatic influence effects similar to the attraction between a rubbed comb and paper snips - we have to compare quantitatively the desk disorder surplus in the gas state with the disco disorder increase of the surroundings produced by the heat of condensation. The latter consists in a transformation of potential energy due to molecular forces into kinetic energy of molecules which can be subsequently "exported" without temperature increase to the environment by the help of molecular collisions. As we live on the ground of an air ocean, every process occurring outside

a closed container (= "submarine" in the air ocean) is subjected to the influence of the hydrostatic pressure of air. Therefore the transition from the liquid to the gas state - which under normal, i.e. atmospheric conditions involves a volume increase by a factor of 10^3, as we have seen in the previous section - requires, in addition to the increase of "internal" potential energy due to the attractive molecular forces, also a certain amount of "external" work against the outer atmospheric pressure. From these purely qualitative considerations, we can deduce two important consequences:

i) As the change in disco disorder a given energy can produce in the surroundings decreases with increasing temperature (because of the shrinking percentage of energy variation) for a sufficiently high temperature the surplus in desk disorder of the gas (relative to the liquid) must overcompensate the disco disorder decrease of the environment caused by the extraction of the necessary (internal and external) transition energy. This means that we can always evaporate a liquid (at a given outer pressure), if we increase the temperature sufficiently.[1] If, on the other hand, the absolute temperature goes to <u>zero</u>, the change in disco disorder of a thermal reservoir induced by the transfer of a <u>fixed</u> amount of kinetic energy, tends to infinity being proportional to the inverse temperature. Therefore, for sufficiently cold systems at fixed pressure the reduction in desk disorder brought about by condensation is always smaller than the disco disorder increase which the heat of condensation creates in the surroundings. Consequently, cold matter is always in a condensed state with dense packing (but not necessarily a solid!), if we fix the pressure.

ii) While the "internal" energy costs for evaporation (corresponding to an increase of molecular potential energy) cannot be altered "from outside", enclosing the system in an "atmospheric submarine" (= closed barostatic container) may change the amount of "external" work (against the pressure) necessary for a transition to the gas state: At reduced pressure the transition energy is lower (and vice versa). Assuming for a while that the difference in desk disorder between liquid and gas is independent of temperature and pressure, at least in a certain interval (a question we shall discuss in the sequel), <u>lowering</u> the pressure should <u>reduce</u> the

temperature of boiling (and vice versa) while its (inverse) ratio to the total energy need for evaporation (also called the evaporation "<u>enthalpy</u>") should remain approximately constant, being proportional to the difference in desk disorder between liquid and gas state. There is a similar principle in physical chemistry called Trouton's rule, which doesn't refer to a given substance under varying pressure, but to different substances under fixed pressure. It states that the quotient of evaporation enthalpy and boiling temperature at atmospheric pressure is, roughly speaking, the same for all substances and therefore a universal constant.

To make a quantitative statement about the difference in desk disorder between liquid and gas, we use the liquid state as a reference and construct a so-called "mongoose lattice" in the gas. (This expression refers to an anecdote told by Prof. E. Rogers in his conference lecture where a man, who feels persecuted by imaginary snakes protects himself by a wooden box containing a mongoose, which is imaginary as well.) The <u>average</u> number of Hamlet-type questions we have to ask for fixing a <u>special</u>, but <u>typical</u> gas configuration in the "mongoose lattice" (which is a (fc) cubic lattice with lattice constant = intermolecular distance in the condensed phase) is of the order of 10/molecule (like in the TV question games!) because under normal conditions a gas occupies the $10^3 = 2^{10}$-fold volume of the corresponding liquid. Therefore in a <u>typical</u> gas configuration every molecule can be found at $\sim 10^3$ sites of the condensed "mongoose lattice" and we expect the universal constant in Trouton's rule, namely h_{ev}/kT_{ev} to be $\approx 0.7 \cdot 10 = 7$ bits/molecule, where h_{ev} is the molecular (not molar) enthalpy of evaporation, T_{ev} the boiling temperature (both at atmospheric pressure) and k the Boltzmann constant. (Of course, $\frac{h_{ev}}{T_{ev}} = s_{gas} - s_{liquid}$ equals the gas-liquid entropy difference/molecule.) While the lattice constant of the condensed "mongoose lattice" is independent of pressure and temperature in the limits of our estimate, the volume of the corresponding gas (at atmospheric pressure) increases with temperature; in the ideal gas approximation (which gives the right order of magnitude even at the point of phase transition) we can calculate the deviation from the Trouton constant 7 bits/molecule if the boiling tem-

perature is not 300 K (table 1).As the desk disorder difference between the two phases, i.e. the information required to fix a special gas configuration relative to the liquid structure depends in a very weak (namely logarithmic) sense on the volume of the gas phase and, as a consequence of the ideal gas law, also very weakly on temperature and pressure, our above made assumption about the independence of disco disorder increase from liquid to gas is indeed valid, together with Trouton's "original" rule, in a rather large neighbourhood of the normal conditions. In our "corrected" version where the Trouton "constant" becomes weakly temperature dependent we can allow a total temperature variation by a factor of 10^3 (the corresponding factor for the evaporation enthalpies is even 10^4!) whereas our rough estimate for the corrected Trouton "constant" deviates[2] only by less than 50% from the experiment! (table2). As a funny conclusion, we can see that Trouton's "constant" has a geophysical origin made clear by our first example: It only depends on the quotient $\bar{h}/h_o$, where $\bar{h}$ is the scale height of the atmosphere (which is independent of its total mass) and h_o is the height of the condensed atmosphere (which is independent of temperature and gravity) taking the equilibrium temperature of the earth's surface as given.

3.3 To Err Is Thermal: Molecules are Sloppy Copyists

One of the greatest problems in teaching thermodynamics and statistical physics is the reconciliation of the universal principle of disorder and decay we call the second law with another (possibly universal) principle, namely darwinian evolution. We have already mentioned the appearance of desk type order in condensed states at sufficiently low temperatures, where the road towards maximal disorder is controlled by the increase in disco disorder. If we take into account also chemical reactions, we find that at a temperature of ~ 300 K and a pressure of $\sim 10^5$ Pa the state of the earth's surface, which has maximal total disorder, is very similar to the primordial atmosphere where all carbon, oxigen and hydrogen probably was in the (fully oxidized) state of lowest energy (H_2O, CO_2, etc.) Therefore, not only the surrounding disco disorder, but also the desk

disorder of the system was high, because these ground states were gases under the (not too abnormal) conditions in the primary atmosphere. Living matter reaches this ground state rather quickly - in a couple of months - if we really enclose it in a thermal equilibrium reservoir at 300 K (which is a completely dark corridor according to Wien's law). The light of the sun which opens an atmospheric window for life has of course a much higher "internal" temperature, namely 6000 K and induces endothermal processes like molecular cleavage and dissociation, because the corresponding gain in desk disorder overcompensates the decrease of disco disorder in the cold environment as a consequence of the high "temperature". (For photochemical reactions which are "far" from equilibrium, we cheat using the above explanation, but it is essentially correct for processes in gas discharges considered later on.) But as the absorption of a solar photon is a rather exceptional event (it comes from a very small solid angle), the molecular "litter" of such a dissociation process, namely the radicals, can easily combine to form a new compound which is practically stable under the given conditions (the temperature of the material environment is 300 K and not 6000 K!). Although the production of metabolic fuel (i.e. molecules which are not in their chemical ground state, i.e. not fully oxidized) by sunlight is a much more complicated process, our naive picture may apply to the chemical reactions in electric gas discharges (lightnings etc.). Stanley Miller's crucial experiment has shown an important yield of both hydrocarbon fuel molecules and small protein catalyst from sparks in a gas atmosphere similar to the primordial one.[3] The subsequent significant step in the evolution of the living substance which M. Eigen and P. Schuster called the Hypercycle can also be understood as a process driven by the creation of disorder. But in contrast to the "equilibrium" situations considered so far, it is not the principle of maximal disorder in the final state which governs this process, but the principle of maximal disorder in a given time interval; i.e. maximal rate of disorder production.[4] The reason for this modified scheme (which is an intermediate one and determines the special chemical path toward final equilibrium, the former being highly nonunique because of the great combinatorial variety in organic chemistry) lies in the conservation of

matter. If a "fast" reaction exhausts all available chemical agents, a slow one which would lead to a final state with greater total disorder cannot proceed. Therefore the obvious limitations in the raw material of evolution lead to chemical darwinism, namely the "survival of the fastest". Another evolutionary principle of great actuality is the conservation of the acquired status quo. It is based on the mechanism of identical reproduction and is in fact a truly quantum mechanical phenomenon. (As a kind of metatheoretical "complementarity", the "fuzzy" space-time properties of quantum objects imply "sharp" and "classical" features in global behaviour like stability and identity!) Every living cell, from yeast to man, contains a fossil vestige from a very early stage of life (the hypercycle?) in form of the transfer RNA molecule.Actually its cloverleaf structure determined by hydrogen bonds of paired RNA nucleotides serves the only purpose of translating, by the help of its unpaired "anticodon" loop, the genetic information on a strand of mRNA into a sequence of single amino acids, each of them being attached to the opposite end of a correponding t-RNA molecule.Because the different t-RNA molecules do not vary to much from yeast to man, one can reconstruct, by statistical means, a common precursor which is thought to have served as an early information carrier because it is in fact itself a piece of RNA. (According to the economy principle of evolution, it has not been thrown away like an old newspaper when its information content got out of interest, but has been "recycled" to serve a new purpose.) As the information stored in a t-RNA molecule is rather low - it contains approximately 70 bases representing 2·70 = 140 bit - the corresponding sequence of amino acids probably did not lead to a protein with strong enzymatic activity. Therefore the reduplication of a primordial t-RNA molecule (which had no transfer function but probably stored "genetic" information) was only based on the attraction between conjugated base pairs. The monomer phosphonucleosids (base + phosphoestered sugar) were aligned by the help of hydrogen bonds in the correct complementary order along the RNA template. The binding energy thus released increased the disco disorder in the solvent (= water) so that this process seemed to maximize total disorder. (After the correct alignment of the monomers, another phosphoester bond linked the nucleosids

together, increasing again, by the released binding energy, the disco disorder in the surrounding water. But what about desk disorder? Making a "mistake" in complementary base pairing (by joining two bases which do not fit together and therefore cannot release energy forming hydrogen bonds) reduces the increase in disco disorder but creates additional desk disorder because the mistake can arise at an arbitrary site of the chain. As the magnitude of desk disorder a single mistake can create in a chain increases with the length of the latter (but only in a weak, i.e. logarithmic way) it follows that there must have been a critical length for the primordial t-RNA where the principle of maximal total disorder creates, on the average, one mistake in every process of "identical" reduplication. If the message coded in the base sequence of the primordial t-RNA were not very redundant - which is not probable because it is very short; in addition we may suppose that it is written in the "actual" genetic code which uses 6 bits, i.e. 64 signs to distinguish between 20 amino acids - then this molecule should not have exceeded its critical length (but probably have come close to it). To make an estimate of this interesting quantity, we first observe that the number of pairs with 3 hydrogen bonds (the so-called cytosine-guanine or C-G pairs), was 51 in the primordial and is 44 in man's t-RNA, while the corresponding number for the adenine-uracil or A-U pairs (with only 2 hydrogen bonds) is 18 resp. 28. (The total number of base pairs, namely 69 resp. 72 is practically, but not precisely equal in both cases.) Thus we can easily see the greater thermodynamical "stability" in the reduplication of the primordial t-RNA molecule which is a consequence of its greater production of disco disorder in the solvent, i.e. the surrounding water. (The advantage of the "actual" distribution of letters - nearer to equipartition - consistsin a greater number of possible messages.) For an explicit estimate of disco disorder produced by a C-G pair with 3 hydrogen bonds (forgetting about the much less frequent A-U variety), we compare with the critical temperature of water which is also determined by the (two) hydrogen bonds of this molecule. At the critical temperature T_{cr} the bound state in the condensed phase disappears, which means that the kinetic energy $\frac{3}{2} k T_{cr}$ of a water molecule equals its binding energy 2ε (where ε

is the energy of a single hydrogen bond). Thus the disco disorder produced by formation of a single C-G bond is $3\varepsilon/0.7\ kT_o$ where $T_o = 300$ K is the temperature of the surrounding solvent (= water). By the help of the rough estimate for ε made above we get for the yield in disco disorder stemming from a correct base pairing the value $\frac{9}{4}\cdot\frac{1}{0.7}\cdot\frac{600}{300} = 6.4$ bit, where $600 = T_{cr}$ is the (approximate) critical temperature of water. As 6.4 bit allow a distinction between ~ 84 possibilities, the reduction of disco disorder production (in the reduplication process of a primordial t-RNA with 84 bases) which is caused by a single mistake, is precisely compensated by the corresponding increase in desk disorder which the unknown location of the defect brings about. In this way we can explain with the help of a quantitative formulation of the second law, why the number of bases in primordial t-RNA ($= \sim 70 \pm 2$) should be smaller, but close to 84! (This remarkable numerical agreement of our estimate with the actual value should be considered as a coincidence.)

It is very fascinating to imagine that the hypercycle (a coupled systen of protein and RNA where RNA synthesizes the protein and the protein catalyzes RNA reduplication) may have transformed a molecular "rabbit", like primordial t-RNA, in spite of its short length, into a carrier of useful information which could be reproduced "thermodynamically" without mistake.[5] But if the critical number of base pairs (where the Second Law produces with certainty at least one average mistake during reduplication) is of the order of 100, how can the genetic information of a virus (10^4 base pairs), of drosophila (10^7 base pairs) and last, not least of man (10^9 base pairs) ever be correctly reproduced? The key to the answer of this important question lies in the exponential increase of the allowed length with the binding energy of the base pairs: By an additional coupling to a protein catalyst (a so-called enzyme), the binding energy difference between correct and incorrect pairing may well be increased by a factor 3 - 4 which appears as an exponent of the critical number of bases and shifts the "small" number 10^2 (for correct enzyme-free reduplication of primordial t-RNA) to the sufficiently large ones like $10^6 - 10^8$ we find in higher organisms (where reduplication is very sophistically controlled by many enzymes).[6] With this beautiful application of simple

mathematics to exciting molecular biology we want to close this article, hoping that disco and desk disorder in the brain of the reader have not yet reached a critical value. Further increase in length would produce with certainty some mistake,but unfurtunately we cannot know in advance where this heppens....

Notes and Remarks

1) This is of course not true if the constant pressure exceeds the critical value. We have not succeeded in explaining critical phenomena in the language of desk and disco disorder.

2)Except for Helium, the calculated enthalpies of evaporation are always smaller than the experimental ones.This may be explained by an additional increase of disco disorder in the gas phase, because some individual modes like molecular rotation etc. can be energetically "frozen" in the liquid state.For water the experimental value lies 80% above the calculated one showing the great barrier effect of the hydrogen bonds for the free molecular movement.As the quantum zero point pressure "inflates" liquid helium, it has a greater desk disorder in the condensed phase than a usual "classical" liquid.Therefore the actual desk disorder increase in evaporation is smaller than expected from our classical considerations.

3) See e.g. Miller,S.,Orgel,L., Origins of life on earth.New Jersey:Prentice Hall 1974

4) This statement seems to contradict some well-established results in nonequilibrium thermodynamics like minimal entropy production at constant fluxes (Glansdorff/Prigogine) as e.g. in a gas burner with steady supply.For nonstationary "growing" systems, the kinetic description of chemical processes far from equilibrium leads to a principle of "survival of the fastest", if we consider an autocatalytic self reproduction like $A_i + B \rightarrowtail 2A_i$ at constant " forces",i.e. concentrations.Assuming a fairly constant entropy production in all concurring single reproduction steps as it would be the case for an ensemble of RNA molecules with different base sequences but of equal length (considered by Eigen and Schuster),then the consequences of the kinetic equations could be formulated in this way.We do not know whether this interpretation is useful or misleading.

5) See e.g. Schuster,P.:Vom Makromolekül zur primitiven Zelle-die Entstehung biologischer Funktion,in Hoppe,W.,Lohmann,W.,Markl,H.,Ziegler,H. eds: Biophysik, Berlin: Springer 1977

6) Of course, mistakes in selfreproduction can never be ruled out with certainty.On the contrary, they play a very important and constructive role in the game of evolution: Although arising randomly (they represent the element of chance, a kind of "free molecular association"), they initiate every step of development.Self-reproduction of the altered base sequence immediately subjects their new properties to the inexorable chemical test of survival where the fastes in reduplication wins. By this strategy of effective self-organisation, the raw material of mistakes, the so called mutants, is transformed into a fitter molecular species.

Table 1

Entropy increase for evaporation at various temperatures and p= 10^5 Pa

boiling temperature T_{ev} (K)	entropy increase per molecule +)
4	2,8 k
9	3,5 k
19	4,2 k
38	4,9 k
75	5,6 k
150	6,3 k
300	7,0 k
600	7,7 k
1200	8,4 k
2400	9,1 k
4800	9,8 k

+) calculated

Table 2

Comparison of the calculated Trouton "constant" with experiment($p=10^5$Pa)

Substance	T_{ev}(Kelvin)	h_{ev}/kT_{ev} $(s_g-s_l)/k$ per molecule		$h_{ev}/T_{ev}(s_g-s_l)$
		1)	2)	
helium	4.25	2.37	2.8	0.85
hydrogen	20.4	5.41	4.2	1.29
argon	87.6	8.55	5.8	1.47
methane	112	8.79	6.0	1.47
ethane	185	9.56	6.4	1.49
propane	231	9.78	6.7	1.46
butane	273	9.87	6.9	1.43
benzene	353	10.5	7.1	1.48
acetic acid	391	7.29	7.2	1.01
mercury	630	11.23	7.7	1.46
potassium	1027	9.08	8.2	1.11
lead	2024	10.65	8.9	1.20
iron	3343	12.75	9.4	1.36
platinum	4573	11.74	9.8	1.20

1) from experiment

2) from Table 1 (interpolated)

T_{ev} boiling temperature at atmospheric pressure $p=10^5$ Pa

h_{ev} enthalpy of evaporation at $p=10^5$ Pa (per molecule)

s_g-s_l molecular entropy increase for evaporation

k Boltzmann constant $1{,}4 \cdot 10^{-23}$ Joule/Kelvin

AN EXPERIMENTAL INVESTIGATION OF THE SECOND LAW OF THERMODYNAMICS: THE STATISTICAL APPROACH

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One of the serious problems facing teachers of physics in secondary school during a short period assigned to primary elements of thermodynamics is a general lack of simple and clear experimental demonstration from which the real meaning of the second law of thermodynamics can be inferred by students themselves.

In the present short note we describe such a kind of the experiment with a few methodological remarks in parallel. The problem how to integrate the experiment with whole teaching program will not be considered here.

In the first chapter of the paper we describe our model system, we call it the block gas, and its statistical properties. This brings in the conception of the Gibbs entropy and the second law of thermodynamics.

In the second chapter we introduce in an intuitive way the Boltzmann distribution and the notion of the "statistical temperature".

1. The block gas and its statistical description

We consider the system of N identical rectangular parallelepipeds each one of the dimensions a x b x c. This is our block gas. In the actual experiment aluminium blocks were used. Their dimensions were a = 3.93 mm, b = 7.00 mm, c = 10.04 mm (see Fig. 1).

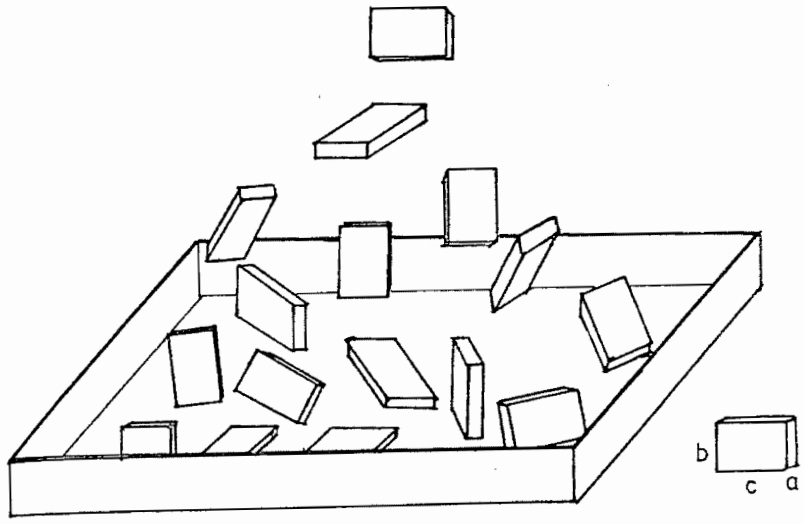

Figure 1. The block gas in thermal movement

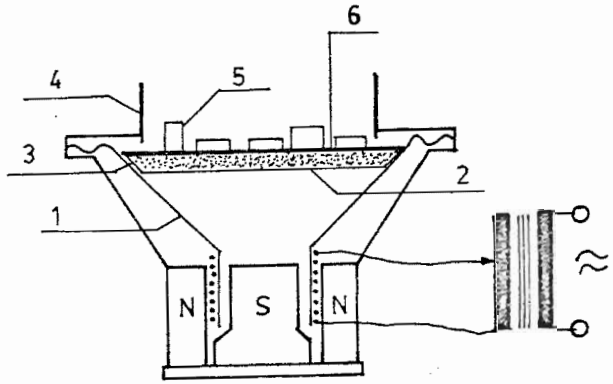

Figure 2. Generator of thermal bath. 1) original membrane of the loudspeaker, 2) styro foam disc 3) glue 4) vessel for block gas 5) block particle 6) hard paper

The blocks were placed upon vibrating membrane of the loudspeaker which simulates the thermal bath (see Fig. 2). Now we can encourage pupils to discover the fundamental laws ruling this simple system. The first discovery is that the classical mechanics is of very little use for such a system. The statistical approach is to be suggested. The three stable states of a single block are characterized by the potential energies:

$$E_a = \frac{1}{2} mga, \quad E_b = \frac{1}{2} mgb, \quad E_c = \frac{1}{2} mgc, \qquad (1.1a)$$

respectively (Fig. 3), where m is mass of a block and g is gravitational acceleration. We will, however, use the system of units in which

$$E_a = a, \qquad E_b = b, \qquad E_c = c. \qquad (1.1b)$$

Such a choice is of course optional.
To study the whole collection of blocks we abruptly switch off the electric current powering the loudspeaker. This corresponds to freezing all the dynamics in one particulary chosen time. It is very easy to notice that the frozen dynamical picture is different for differently chosen amplitudes of the vibration of the membrane. Therefore, to distinguish the systems with different strengths of thermal bath we will introduce a parameter Θ (the statistical temperature). The precize meaning of Θ will be clarified in the next section (see also Figure 4).

Now we count the population numbers $N_i = N_a, N_b, N_c$ of blocks being in E_a, E_b, E_c energy states, respectively. The numbers N_i for N large enough define probability distribution

$$p_i(\Theta) = N_i / N. \qquad (1.2)$$

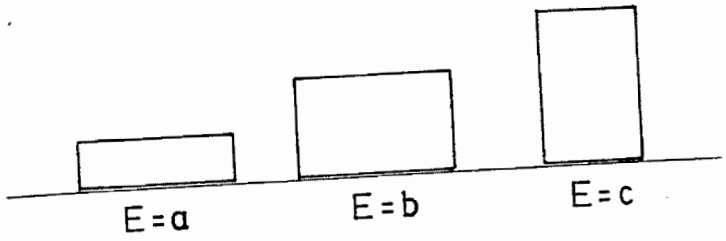

Figure 3. Stable states of a single block

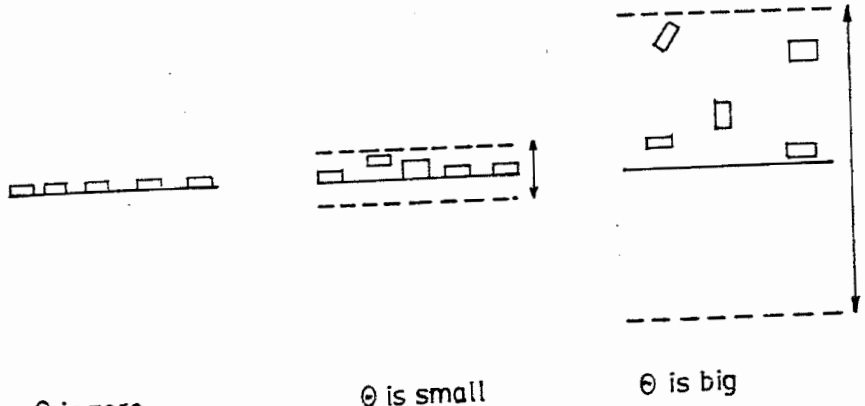

Figure 4. Different situations for different amplitudes of membrane vibrations (different Θ).

Actually for N hot very large we use the total values N_i taken from many experiments performed at the identical conditions. Thus p_a is probability of finding any chosen block in state characterized by energy E_a and so on. The probability distribution is dependent on θ. To find the law governing this dependence we repeat all the experiment for different θ. We calculate the average energy per block

$$\langle E \rangle_\theta = \frac{1}{N}\left(N_a E_a + N_b E_b + N_c E_c\right) \qquad (1.3)$$

for a chosen value of θ. Two experimental results from 10 performed runs are presented in Table 1. The power of normally performing loudspeaker was 15W, N was 100.

Now the very serious question arises: Are our results completly random or is there some inherent universality in them?

In other words we can ask what is the influence of the initial state (before the loudspeaker is switched on) of the collection of blocks and the influence of the exact value of freeze time on the obtained data i.e. on $p_i(\theta)$ and $\langle E \rangle_\theta$ (for a fixed value of θ i.e. for particularly chosen power discipated by the loud speaker)?

It is necessary to perform many additional runs for different initial states and different freeze times. The conclusion is simple. Provided the time during which the the whole vibrates is not too short (3-5 s) the results for p_i and $\langle E \rangle$ are always virtually the same. Of course there is a small measure of randomness from one statistical sample to another as it should be. However, very definitely there is no trace of any hidden variables.

As the value of the parameter θ increases we find that the state of the system approaches the full chaos i.e. $p_i = 1/3$ for i = a, b, c.

On the other hand for very small values of θ there is order in the system i.e., $p_a = 1$, $p_b = 0$, $p_c = 0$.

These findings agree well with the common experience and with intuitive knowledge of basic laws of nature. Now it be tempting to find some measure to the chaos η. By making a simple guess our first choice will be

$$\tilde{\eta} = N_a \cdot N_b \cdot N_c \qquad (1.4)$$

The Fig. 5 can serve as intuitive explanation for this guess. However the eq. (1.4) is not good enough because for any $N_i = 0$ also $\tilde{\eta} = 0$ independently on the values of two others N-s. The second simplest choice for η is

$$\tilde{\eta} = N_a^{-N_a} \cdot N_b^{-N_b} \cdot N_c^{-N_c} \qquad (1.5)$$

where $N_a + N_b + N_c = N = \text{const}$. The extremal value of corresponds to $N_a = N_b = N_c$. If we chose to work with the relative population numbers $n_a = N_a/N, \ldots$ we write down

$$\tilde{\eta} = n_a^{-n_a} \cdot n_b^{-n_b} \cdot n_c^{-n_c} \qquad (1.6)$$

In the logarithmic scale the formula (1.6) takes the following form

$$\eta = -\frac{N_a}{N}\ln\frac{N_a}{N} - \frac{N_b}{N}\ln\frac{N_b}{N} - \frac{N_c}{N}\ln\frac{N_c}{N} \qquad (1.7)$$

which is Gibbs' entropy functional.

Now we can continue our investigation. For a fixed value of average energy ($\langle E \rangle = \text{constant}$) there is only one independent variable in our problem, say N_b. Thus

$$N_a = \frac{N\left(\langle E \rangle - E_c\right) - N_b\left(E_b - E_c\right)}{E_a - E_c}, \qquad (1.8)$$

$$N_c = N - N_a - N_b.$$

The relation $\langle E \rangle = \text{const}$ determines our system to be isolated. The Fig. 6a and Fig. 6b show the dependence of the functional η on the value of N_b for $\langle E \rangle = 4.53$ and 5.01 respectively. The maximal value of η corresponds to spontaneously formed configurations (see Table). Thus the maximal chaos for

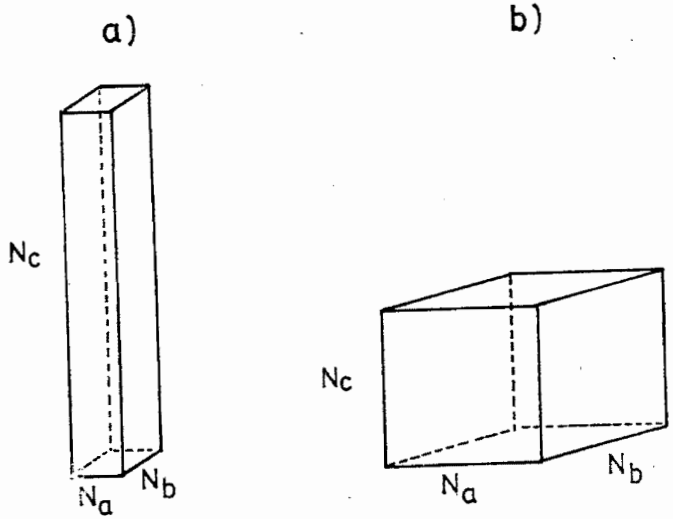

Figure 5. The first primitive measure of the chaos $\tilde{\eta} = N_a N_b N_c$
small chaos b) large chaos

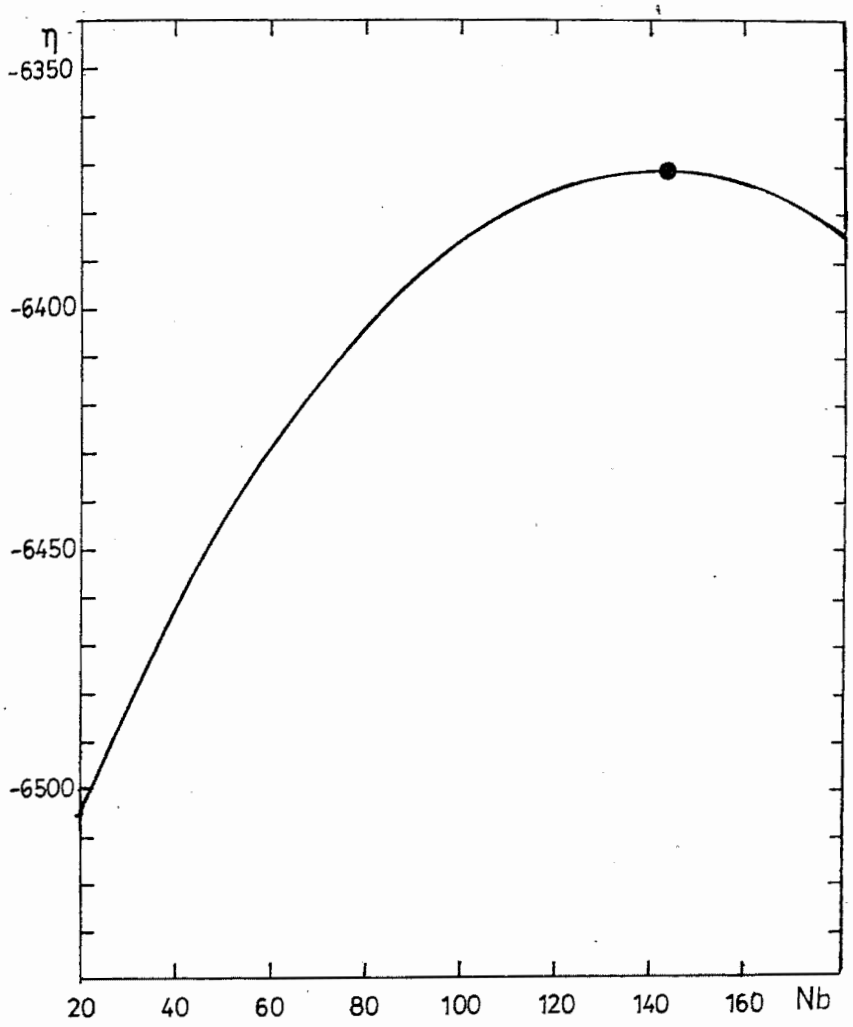

Figure 6a.

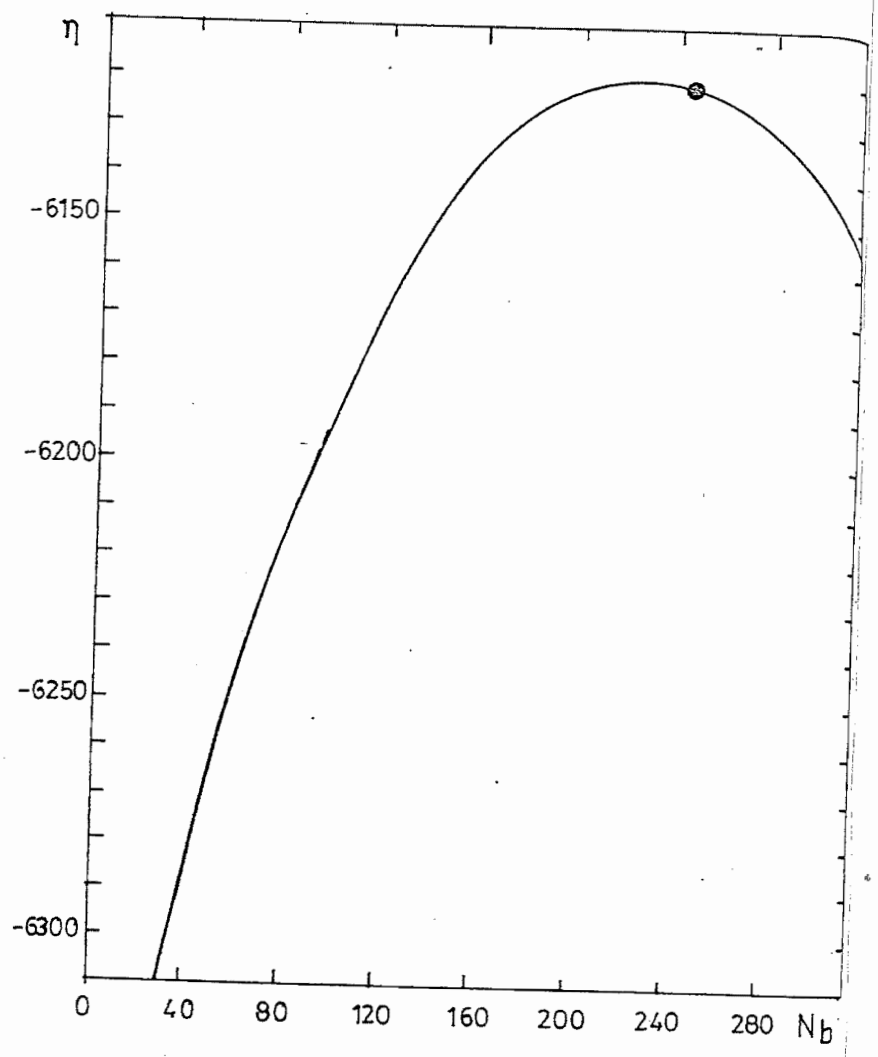

Figure 6b.

a given fixed value of $\langle E \rangle$ is being realized for our natural equilibrium state. We can rephrase the last statement in the following way:
In dependently of the initial condition a system with a fixed energy undergoes an evolution in such a way that the chaos (entropy) is maximalized. This is second law of thermodynamics.

Table 1

J [A]	N_a	N_b	N_c	$\langle E \rangle$ [mm]	ϑ [mm]
2.15	830	144	26	4.53	0.36
2.40	689	245	66	5.09	0.51

Repeating whole procedure from the begining few times the fluctuations of the entropy can be shown. Changing the sign of η in the Fig. 6 ab we can introduce a concept of thermodynamical potential and explain its meaning.

Boltzmann distribution and related problems

The results collected in the Table 1 can be used for derivation of the single particle distribution function. Drawing the population numbers v.s. potential energy (taken from the Table 1) we show that they became to be equal (Fig. 7) if ϑ increases. Looking for the analytic form of this law we map the Fig. 7 into the logarithmic scale (see Figure 8). We obtain straight lines with the slopes depending on the amplitude of loudspeaker (Fig. 8). The increase of the slope α corresponds to the decrease of ϑ . Now we can precisely define the parameter ϑ:

$$\vartheta = (\tan \alpha)^{-1} \qquad (2.1)$$

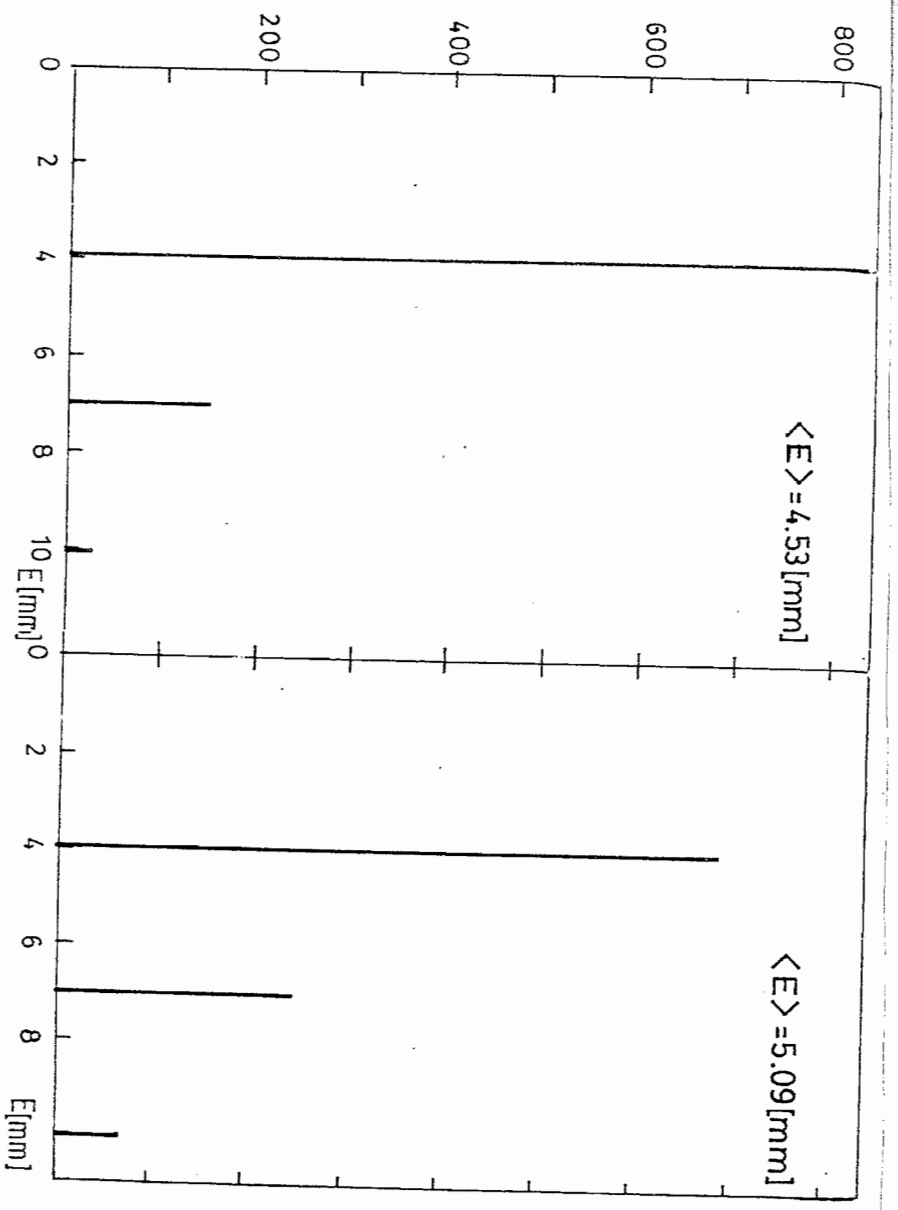

Figure 7.

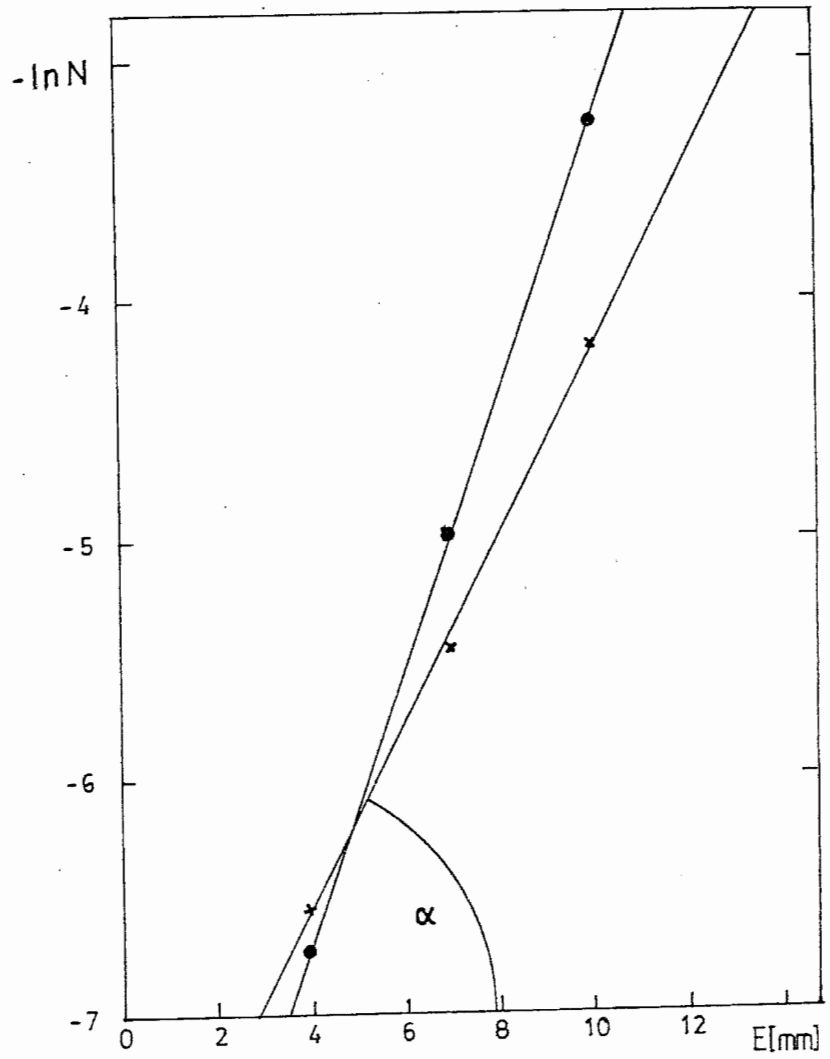

Figure 8

and finally we write down the formula for the population number

$$N_i \sim \exp(-E_i/\Theta). \qquad (2.2)$$

Using the values of the average energy and the corresponding values of Θ we calculate the heat capacity of the considered system

$$C = \frac{\Delta \langle E \rangle}{\Delta \Theta} = 3.73 . \qquad (2.3)$$

The last problem which we discuss is measurement of Θ. The values of Θ from the Table 1 were calculated with the aid of formula (2.1) and Fig. 8. Can we measure Θ directly? It has been discovered by student Robert Konieczny that it is proportional to the fourth power of the power current of the loudspeaker:

$$\Theta = k \cdot I^4 \qquad (3.3)$$

where k plays the role of the Boltzmann constant. Its value is 1/13 $mm \cdot A^{-4}$. Thanking the relation (2.3) the Θ parameter can be measure directly with the aid of ampermeter.

The derivation of eq. (2.2) bases on the stright line through the three points. So, this derivation is not too reliable. It is possible to perform an analogous experiment with the subset of blocks which is more reliable. This experiment will be described in the materials of the conference "Physics in the Higher Schools - Rackova Dolina 1983".

Finally we would like to make a few technical remarks. In order to freeze time the power current must be turned off rapidly. If the current decreases slowly, then we observe that all particles reach the ground state E_a. The loudspeaker must be fixed in the horizontal position. The block gas must not be too dense, otherwise one would get states with blocks stacked one on the other, which cannot be classified by E_i numbers.

WHY DOES RUBBER STRETCH?

(an example of simple statistical mechanics)

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History

Rubber is curious stuff. Stretch a rubber band suddenly, then touch it to your lips: it feels warm. Adiabatic stretching of a rubber band produces an increase of temperature, like adiabatic compression of a gas. - If you warm a stretched rubber string, it shrinks, like a backward thermometer! - Rubber behaves in many respects as a gas in reverse, and this behaviour is worth of investigation.

The earliest investigation of rubber elasticity was reported by J.Gough (1805, Mem. Lit. Phil. Soc. Manchester 1, 288). The more detailed study of the thermal behaviour of rubber is due to J.P.Joule (1859, Phil. Transactions, Royal Society, London A 149, 91-131). This investigation used vulcanized rubber, made available by the work of Goodyear. H.Staudinger (1927, Kautschuk 63) established the first clear evidence for macromolecules in rubber. Somewhat later K.H.Meyer, G. von Susich and E.Valko gave a molecular explanation of rubber elasticity (1932, Kolloidzeitschrift 59, 208): it was proposed that internal rotation about the C-C bonds of the chain would permit the macromolecule to assume randomly coiled conformations. When the system was stretched, the restoring force was conceived to arise because the thermal distribution of conformations was being distorted. The molecular chains were considered to confer on the material a kinetic elasticity similar to the kinetic elasticity of a gas. (C.Price, 1976, Proc. Royal Society, London, A 351, 331)

When one tries to introduce the concept of entropy in school, the abstractness of axiomatic thermodynamics is ill-suited to pupils, who find it easier to think more concretely. Simple molecular models like the kinetic model of the ideal gas (PSSC, Sexl) and the Einstein model of a crystal (Nuffield, E.Tóth) have been exploited in different approaches. The aim of this report is to explore the chain model of macromolecules, in order add to the variety of materials that can usefully be studied.

Empirical Behaviour

If one presses a gas in a container, it gets compressed easily at first, and then it becomes harder and harder to compress, as you approach the density of the fluid.

When one pulls on a rubber band, it stretches easily at first, and then becomes harder and harder to stretch, until at a relative extension of several hundred percent it becomes extremely hard to stretch further, and suffers brittle fracture. Figure 1. shows a typical force-relative extension curve.

If a band is kept at a fixed relative extension, and is warmed, the tension increases, as shown in Figure 2. Similarly, a band supporting a weight will shrink and lift the weight if warmed. This behaviour of course relates to the warming or cooling of rubber when stretched or relaxed, mentioned previously.

Phenomenological Thermodynamics

Let us describe briefly the thermodynamics of rubber, meant strictly for adult experts.

In the case of reversible isothermal stretching, $Q = T\Delta S$, and the work performed $W = \text{Force} \cdot \Delta L$, the volume varition being negligible. Consequently, using the first law:

$$\Delta E = T\Delta S + \text{Force} \cdot \Delta L \qquad (*)$$

The variation of the free energy $F = E - TS$ is thus $\Delta F = \Delta E - T\Delta S - S\Delta T = \text{Force} \cdot \Delta L - S\Delta T$. Consequently:

$$\left(\frac{\partial F}{\partial T}\right)_L = -S \text{ and } \left(\frac{\partial F}{\partial L}\right)_T = \text{Force}.$$

From $\frac{\partial^2 F}{\partial L \partial T} = \frac{\partial^2 F}{\partial T \partial L}$ one gets the Maxwell relation

$$-\left(\frac{\partial S}{\partial L}\right)_T = \left(\frac{\partial \text{Force}}{\partial T}\right)_L . \qquad (*^*)$$

Rewriting equation (*) as the derivative with respect to length for isothermal stretching:

$$\left(\frac{\partial E}{\partial L}\right)_T = T\left(\frac{\partial S}{\partial L}\right)_T + \text{Force},$$

and by making use of the Maxwell relation ($*^*$), we obtain:

$$\text{Force} = \left(\frac{\partial E}{\partial L}\right)_T - T\left(\frac{\partial S}{\partial L}\right)_T .$$

Thus the force required to stretch the rubber comes from two terms. The first term takes into account change of internal energy. The second relaties to the decrease of entropy in the stretched rubber.

Force-temperature curves can be obtained empirically (Figure 2). The force extrapolated to T=0 gives the energy contribution $(\partial E/\partial L)_T$. In this way the energy contribution and entropy contribution to rubber elasticity can be separated (Figure 3), and it turns out that the energy contribution is practically constant and it is significant only in the case of small dilatations. More exact measurements of P.J.Flory (1976, Proc. Royal Society, London A 351, 351) indicated that the energy contribution to rubber elasticity is only about 11-18 %. The main contribution is due to entropy

elasticity.

This justifies using the approximation

$$\left(\frac{\partial E}{\partial L}\right)_T = 0,$$

i.e. the energy of "ideal" rubber is independent its dilatation. This should remind us of the parallel result:

$$\left(\frac{\partial E}{\partial V}\right)_T = 0$$

for an "ideal" gas. We shall exploit this approximation to build up a molecular model for "ideal" rubber, which is simple enough to be used in schools, but realistic enough to reflect the strange thermal behaviour of rubber qualitatively or even semiquantitatively.

The Macromolecular Structure of Rubber

Raw rubber or latex consists of polymer chains of the isopreme monomer C_5H_8. Each monomer contains a C-C σ-bond about which rotation can occur, and thus the chains can assume a randomly coiled form if the temperature is not too low (at low temperature rubber becomes glassy). Latex does not exhibit the properties of rubber, which are induced by "vulcanising" with sulphur so as to cross-link the chains at intervale with sulphur bridges. Various degrees of such vulcanisation are possible, and determine the maximum relative stretch, through differences in the average number N of monomer links in chains between cross-links.

When rubber is stretched as much as possible, the chains between cross-links become almost straight, and the force begins to deform covalent bonds, not to act against the tendency of C-C bonds to rotate thermally and coil the chains. It is worth noting that X-ray photographs of rubber show structure in stretched rubber absent in the relaxed state (Nuffield Advanced Physics, Unit 1, Materials and Structure).

The Model of Rubber in One Dimension

Let us assume that the rubber chain between two sulphur bridges is made of N rigid units, like N linked paper clips, each of length a. The maximum stretched length is $L_{max} = Na$, but if the chains coil randomly the actual length L_{av} is shorter.

Let us make N steps, along a one dimensional path. Each step $a_i = \pm a$, so

$$L = \sum_{i=1}^{N} a_i$$

$$L^2 = \left(\sum_{i=1}^{N} a_i\right)^2 = \sum_i a_i^2 + 2\sum_{i<j} a_i a_j = a^2\left(N + 2\sum_{i<j}(\pm 1)\right).$$

The second sum contains about as many +1 terms as -1 terms in the case of complete disorder, so its value is negligible for large N. Thus,

$$L^2 = a^2 N,$$

$$L_{av} = a\sqrt{N}.$$

By comparing the length L_{av} of an unstretched rubber band to the length L_{max} of a fully stretched one, a simple rough estimate of N is possible.

$$\frac{L_{max}}{L_{av}} = \frac{aN}{a\sqrt{N}} = \sqrt{N}.$$

Values of between 4 and 6 are common, and thus N is of the order 25 or so.

This conclusion is valid also in two or three dimensions, where $\underline{a}_i$ are vectors of the length a and $\Sigma \underline{a}_i . \underline{a}_j = 0$. Pupils may try such random walks themselves with dice, pencil and paper, or a computer simulation can be shown. A chain of paperclips on an overhead projector is a useful teaching device.

A model chain has N units. In one dimension each unit may have 2 orientations. That makes 2^N orientations, 2^N configuration microstates altogether, each of the same energy. So the configuration entropy of the chain is $S_{conf} = k \ln 2^N = k N \ln 2$. It is proportional to the stretched length of the chain.

If the chain is fully stretched, all the units are in the same direction, and this is a unique microstate with $S_{conf} = k \ln 1 = 0$. In case of sudden (adiabatic) full stretching $\Delta S_{conf} = - k N \ln 2$. The overall entropy cannot decrease, $S = S_{conf} + S_{vibr} = \text{const}$, so the vibration entropy S_{vibr} must be increased: $\Delta S_{vibr} = k N \ln 2$. This can produced by energy gain, covered by the dilatation work:

$$Q = T\Delta S = k N T \ln 2.$$

This energy increases the intensity of molecular vibrations and the rubber becomes warm. If a monomer unit is made of n linear oscillators, the vibration energy of the chain, consisting N monomers is

$$E_{vibr} = NnkT,$$

giving a heat capacity

$$C = Nnk.$$

The measured specific heat of rubber is $c = 2$ kJ $kg^{-1}K^{-1}$. One monomer C_5H_8 has a molecular weight equal to 68 daltons, i.e. $m \simeq 10^{-25}$ kg, so the measured heat capacity of a monomer is

$$nk = 2.10^{-25} \text{ kJ/K},$$

which gives $n \simeq 15$ for the number of vibrational degrees of freedom of a rubber monomer (practically equal to the

number of atoms n = 13 in the monomer). So the heat income $Q = k N T \ln 2$ produces a temperature increase

$$\Delta T = \frac{Q}{C} = \frac{NkT \ln 2}{nNk} = \frac{T}{n} \ln 2$$

which is of the order of 15 C. This calculation can be tested experimentally. It is more convenient to let a rubber band at room temperature, stretched to its maximum length, shrink suddenly, when it cools down, and the temperature change can be measured by a thermocouple. Empirically, ΔT is of the order of a few degrees, so that the one dimensional estimation is in error by one order of magnitude.

For a specific rubber band of mass $25 \cdot 10^{-5}$kg an average force of 5N was needed for a dilatation of 0.2 m. This means that the work performed was 1.0 J. If this gives the heat for vibrations, with a specific heat $c = 2$ kJ $kg^{-1}K^{-1}$ one calculates $\Delta T = 2K$.

Variation of Force with Length and Temperature

In a specific configuration of the one dimensional chain, let us denote the number of "forward step" monomers by N_+ and the number of "backward step" monomers by N_-.

$$N_+ + N_- = N = \frac{L_{max}}{a}$$

$$N_+ - N_- = \frac{L}{a} = x.$$

The specific macrostate of l-ngth $L = ax$ is realized by

$$W(x) = \binom{N}{N_+} = \binom{N}{\frac{N+x}{2}}$$

different configurations (microstates).

Let us increase the number of "forward step" monomers to $N_+ + 1$. The number of backward step" monomers increases to $N_- - 1$. The length of the chain increases by $\Delta L = a\Delta x = 2a$. What is the change of $W(x)$?

$$W(x+2) = \frac{N}{(N_+ + 1)!(N_- - 1)!} = \frac{N_-}{N_+ + 1} \cdot \frac{N!}{N_+! N_-!} =$$

$$= \frac{N_-}{N_+ + 1} W(x) \approx \frac{N_-}{N_+} W(x),$$

consequently

$$\frac{W(x+2)}{W(x)} \approx \frac{N_-}{N_+} = \frac{\frac{1}{2}(N-x)}{\frac{1}{2}(N+x)} = \frac{1-\frac{x}{N}}{1+\frac{x}{N}}.$$

If one makes this jump of monomers r times,

$$\frac{Z(x+2r)}{Z(x)} \approx \left(\frac{1-\frac{x}{N}}{1+\frac{x}{N}}\right)^r.$$

The corresponding entropy change is equal to

$$\Delta S = k \frac{\ln W(x+2r)}{\ln W(x)} = kr \ln \frac{1-\frac{x}{N}}{1+\frac{x}{N}}$$

This result can be developed to account fairly well for the form of the force extension curve in Figure 1. However, we shall consider only small extensions for which one can make use of the approximation

$$\ln (1+\varepsilon) \approx \varepsilon \qquad \text{for } \varepsilon \ll 1.$$

obtaining

$$\Delta S \approx -2kr\frac{x}{N}.$$

Changing one "backward step" to a "forward step" means stretching of the chain with length $L = ax$ by $\Delta L = 2ar$, so one gets

$$\Delta S = -\frac{k}{Na^2} L\Delta L$$

The free energy $F = E - TS$ of the "ideal" rubber model ($\Delta E = 0$) changes in the case of isothermal stretching ($T = \text{const}$) by

$$\Delta F = -T\Delta S = \frac{kT}{Na^2} L\Delta L.$$

This change of free energy is due to the performed work

$$\Delta F = \text{Force} \cdot \Delta L,$$

consequently

$$\text{Force} = \frac{kT}{Na^2} L.$$

The force constant is, as in the above equation, proportional to the absolute temperature, and this can be tested experimentally as in Figure 2. It turns out that the force constant D is

$$D = \frac{kT}{\langle L^2 \rangle}.$$

Let us hang a weight of mass m on a rubber band. It will be stretched by z:

$$Dz = mg,$$

so

$$z = mg/D = mg\langle L^2 \rangle / kT.$$

The contraction of a stretched rubber band when warmed is just the opposite to the behaviour of most solids. This anomalous behaviour is due to the entropy elasticity, in contrast to the energy elasticity of Einstein Solids. Compare the behaviour of a mercury thermometer to a rubber thermometer!

The Model of Rubber in Three Dimensions

Let us take a Rubik's Snake, made of N = 24 pieces. Each piece may have 4 different positions with respect to the former ones. That makes $W = 4^{23} = 7.10^{13}$ configurations altogether.

Let us generalize the rubber model to 3 dimensions. It does not give qualitatively new effects, and we mention it only for completeness.

In the sp^3 hybrid state the valence angle of C-C bonds makes an angle of 109.5°. The configuration of the central C-C bond in a $CH_3-CH_2-C-CH_2-CH_3$ molecule may have 3 different positions (Figure 4), so the number of different configurations of a long $CH_3-(CH_2)_{N-1}-CH_3$ chain is $Z=3^N$, consequently $S = kN \ln 3 = 1.09\ xkN \approx kN$. This is true only if the trans and cis configurations are of equal energy. In reality, due to Pauli exclusion, the trans configuration is lower by ε_o than the cis configuration ($\varepsilon_o \approx 12$ kJ/mol = 0.02 aJ, to be compared with kT = 0.004 aJ at room temperature), so two cis configurations are by $\exp(-\varepsilon_o/kT) = 0.0067$ less abundant than the trans configuration. To calculate the mean square chain length, we write as before

$$\underline{L} = \sum_i \underline{a}_i, \qquad L^2 = Na^2 + 2\sum_{i,j} \underline{a}_i \underline{a}_j .$$

We have to calculate the sum of $\underline{a}_i \underline{a}_j$ ba taking into account, that the angle between $\underline{a}_i$ and $\underline{a}_{i+1}$ makes $\Theta = 109.50$, and the azimuth angle ϕ may take the value $\phi = 0$ and also the value of $\phi = \pm 120$, but with the last mentioned having a smaller probability $\exp(-\varepsilon_o/kT)$. Thus the average length of the

chain depends on some function f(T) of temperature.

$$L^2 = Na^2 f(T).$$

A Rubik's Snake has fewer than 4^{23} configurations, because self-crossing configurations are excluded. Instead of $\langle L^2 \rangle = Na^2 f(T)$ computer simulations gave for large N values

$$\langle L^2 \rangle = N^{3/2} a^2 f(T) \quad \text{in 2 dimensions}$$
$$\langle L^2 \rangle = N^{6/5} a^2 f(T) \quad \text{in 3 dimensions}$$
$$\langle L^2 \rangle = N a^2 f(T) \quad \text{in 4 dimensions.}$$

*

The abundance of configurations of different lengths in three dimension can be obtained from the products of the corresponding distributions in one dimension. We have seen that

$$\Delta \ln W(L) = -\frac{rx}{N} = -\frac{L\Delta L}{Na^2} = -\frac{L\Delta L}{\langle L^2 \rangle}$$

so

$$W(L) = C \exp\left(-\frac{L^2}{2\Delta L^2}\right)$$

in one dimension. Consequently,

$$W(X,Y,Z) = C \exp\left(-\frac{X^2}{2\langle X^2\rangle} \exp -\frac{Y^2}{2\langle Y^2\rangle} \exp -\frac{Z^2}{2\langle Z^2\rangle}\right) =$$
$$= C \exp\left(-\frac{\frac{3}{2}(X^2+Y^2+Z^2)}{\langle L^2\rangle}\right) =$$
$$= C \exp\left(-3L^2/2\langle L^2\rangle\right)$$

in three dimensions. From this one gets the L dependence of entropy and free energy:

$$F(L) = F(0) - \frac{3kT}{2\langle L^2\rangle} L^2 = F(0) - \frac{1}{2} D L^2,$$

giving the force constant

$$D = \frac{3kT}{N^{6/5} a^2 f(T)}$$

for rubber. It is not very different from the one dimensional model. The empirical correction factor is $f(T) = 4{,}5$ for rubber at room temperature.

Curvature of Force-Extension Curve at Small Extensions

In rubber the molecular chains have a random distribution. If the volume of rubber remains the same, a relative stretching λ of the rubber band means a shortening of the chains perpendicular to the direction of the band by $\sqrt{\lambda}$. Thus the decrease in entropy due to stretching is partly offset by an increase due to lateral contraction. It is this which makes the force extension curve begin to rise more steeply than it does at moderate extensions.

The overall free energy change in three dimensions turns out to be

$$F(\lambda) = K - \frac{kT}{2}\left(\lambda^2 + \frac{2}{\lambda}\right).$$

Hooke's Law is not valid. In the case of maximum extension $\lambda = \sqrt{N}$, so

$$Q = F(0) - F(\sqrt{N}) = \frac{kT}{2}\left(N + \frac{2}{\sqrt{N}} - 3\right) = NkT\left(0.5 + N^{-3/2} - 1.5\, N^{-1}\right)$$

which gives a Q value smaller by a factor 2/3 than in the one dimensional model.

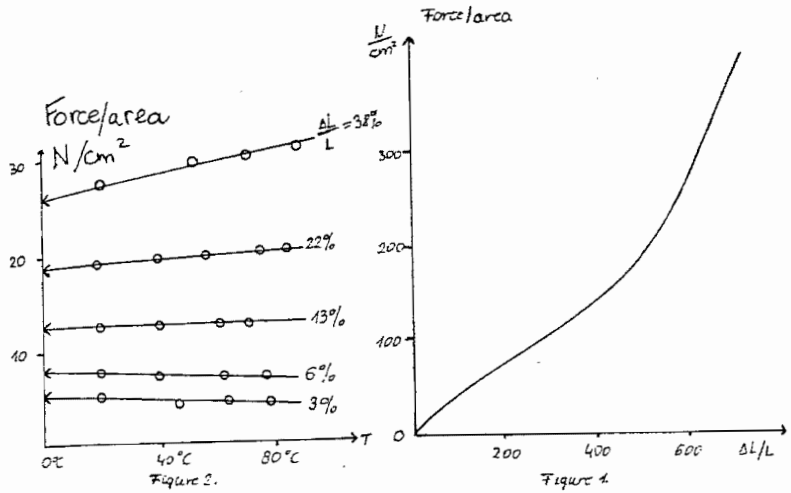

Figure 2.

Figure 1.

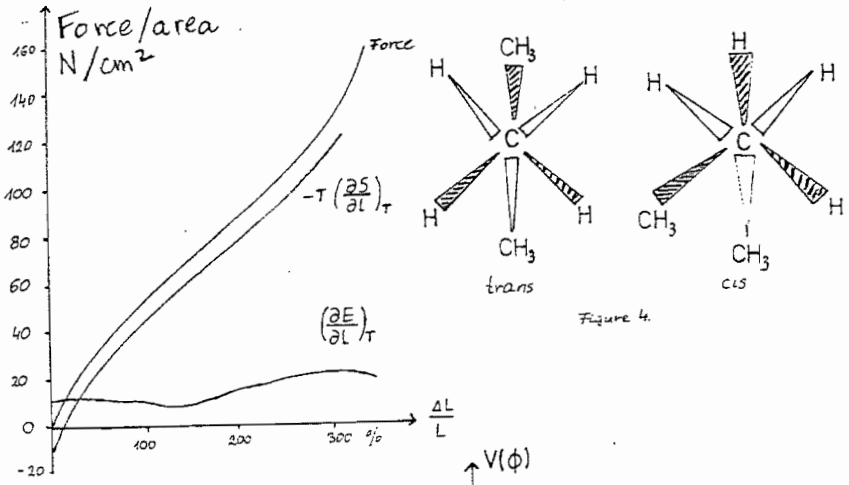

Figure 3.

Figure 4.

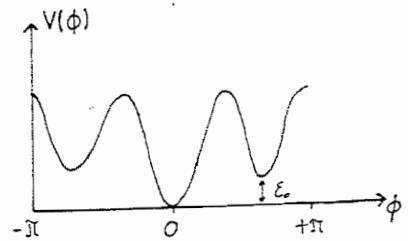

Figure 5.

Conclusion

Experiments with rubber are easy to do, and the results are interesting and suprising. They depend in an important and straightforward way on entropy changes.

Not all the arguments given here easy enough for use in school, but are presented for the information of teachers. However, the random walk argument, especially in one dimension, is not too difficult, and gives an estimate of a microscopic parameter N from microscopic behaviour. The one dimensional argument for the form of the form extension curve is harder, but may be worth attempting with some students. The use of a simple entropy estimate to explain the temperature change of stretching or contraction offers a valuable further instance of the power of statistical interpretations of entropy.

TAK BĘDZIEMY BADAĆ ROZCHODZENIE SIĘ WONNEJ SUBSTANCJI W KLASIE.
TU JA WYDRYWAM ZA POMOCĄ NOSÓW.
TU ROZPYLAMY BADANĄ SUBSTANCJĘ.

Fyzika, grade 6
by J. Ginter, Poland

SIMULATION OF A DISORDERED SYSTEM

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A situation encountered in teaching entropy to school children is to explain how ordered sytems become disordered and why such processes are usually irreversible - Rubik's cube not withstanding. One can of course demonstrate this in many ways - by actual experiments like the mixing of a drop of ink in a beaker of water, or by simulations like shaking two lots of marbles of different colours in a tray. In my opinion however, these are not completely satisfactory as they do not touch upon what I consider to be the heart of the problem. After all, macroscopic disorder could arise either because of the random behaviour of the microscopic constituents themselves, or, despite the microscopic units being regular in their behaviour, because of the large numbers of such constituents that are involved. How do the students convince themselves that macroscopic disorder can emerge from microscopic behaviour which is regular and not chaotic?

It would seem that the Baker transformations offer a basis for such a simulation. The transformations get their name from the fact that they can be considered to be a mathematical representation of the way in which a baker mixes dough before baking bread.

In two dimensions the Baker transformations can be described in the following fashion (see figure 1) : start with a unit square, stretch it horizontally to twice its length while preserving its area, cut the resulting rectangle vertically in half and then stack the right half over the left to recover the unit square. Except for an initial distribution of points of measure zero, repeated application of this process can be shown to lead to stochastic behaviour. For the transformations to yield the desired result, it is necessary to start with a set of points the ratio of whose x- and y-coordinates are irrational numbers. Since a computer

can only perform arithmetic on a finite string of numbers, a simulation of the kind we want based on the Baker transformations is doomed to failure.

Let us therefore consider another set of transformations - the Arnold Cat map, to see if they serve our purpose. For this we start with a 2 x 2 matrix of positive elements chosen such that its eigenvalues are irrational numbers, for example :

$$\begin{pmatrix} 1 & 1 \\ 1 & 2 \end{pmatrix}$$

whose eigenvalues are $(3\pm\sqrt{5})/2$. We divide the whole of the positive quadrant into a set of equivalent unit squares. We start with a point P_o with coordinates (x_o,y_o) in the unit cell defined by $0 \leqslant x_o,y_o \leqslant 1$ (see figure 2). We now transform to the point P'_o with coordinates (x'_o,y'_o) by means of the transformations :

$$\begin{pmatrix} x'_i \\ y'_i \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 2 \end{pmatrix} \begin{pmatrix} x_i \\ y_i \end{pmatrix}$$

$i = 0,1,2,\ldots$. From the point P'_o we go to the equivalent point P_1 in the unit cell with coordinates (x_1,y_1) given by :

$$x_{i+1} = x'_i - \text{int}(x'_i)$$
$$y_{i+1} = y'_i - \text{int}(y'_i)$$

where int(x) denotes the integer part of x.

It is straight forward to program these transformations on a microcomputer and provided we choose (x_o,y_o) such that their ratio is as incommensurable as possible, the system point can be seen to gradually and in a chaotic fashion cover the whole of the unit cell - the system looks as if it is ergodic. Here then we have an example of a system governed by a set of well defined transformations which nevertheless possesses chaotic behaviour. One can stop the program after a certain number of cycles and apply the inverse transformations repeatedly to the system point. We shall then see that the system point, instead of retracing its path, sets off on an independent chaotic route. This is because the computer, at each step, loses some of the information that is necessary in order to exactly reverse the transformations because of round-off error in its arithmetic. The program therefore also simulates irreversibility.

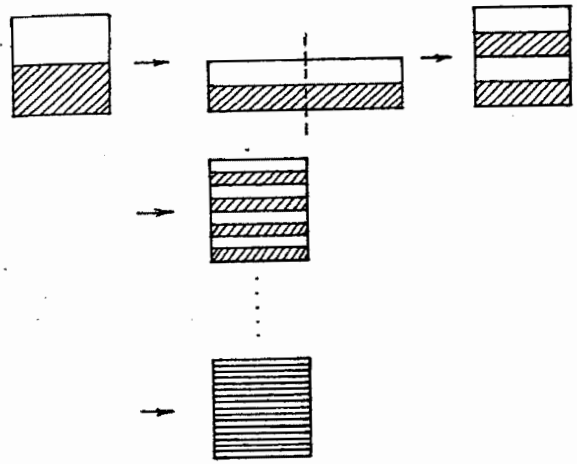


Figure 1.

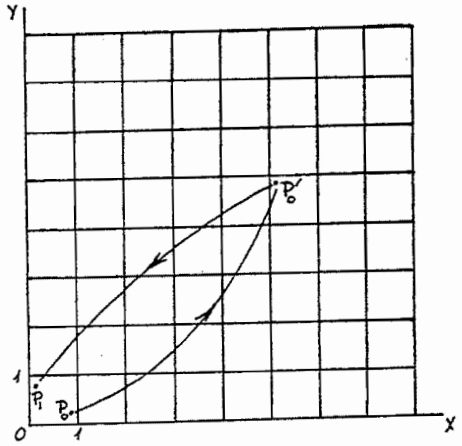
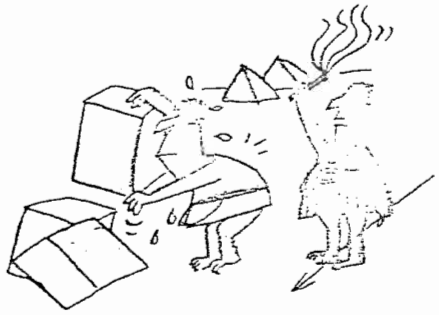


Figure 2.

La guerre du feu.



Complément énergétique indispensable pendant longtemps : l'esclavage

Au XVI[e] siècle en Angleterre : plus de forêt.

SCHOOL

ENERGY IS A STATUS SYMBOL FOR GROWNUPS.

Authentic Hungarian pupil's opinion

ENERGY IS MORE DIFFICULT CONCEPT THAN ENTROPY.

John Lewis

AMONG THE MANY QUANTITIES, INTRODUCED BY PHYSICS, LIKE ENERGY, MOMENTUM, CHARGE OR TEMPERATURE, THERE IS ONE, WHICH IS CONSIDERED TO BE MYSTERIOUS AND UNUNDERSTANDABLE; IT IS THE ENTROPY.

Roman U. Sexl

WE MAY HOPE THAT WE SHALL BE ABLE TO REDUCE THE ANTIPATHY TO ENTROPY ON THE SAME WAY AS THE PSYCHOANALYST HOPES TO CURE HIS PATIENT: LET US TRY TO MAKE OPEN THE ORIGINS OF THIS DISEASE.

Friedrich Herrmann

THE STRONGHOLD OF THE DETERMINISTIC SENTIMENTS IS THE ANTIPATHY TO THE IDEA OF CHANCE.

William James

A YOUNG MAN - FULL OF FIRE - JOINED AN EDUCATIONAL CONFERENCE HOPING TO SUGGEST A PROMISING BUT UNUSUAL CHANGE OF TEACHING. HE MADE HIS SUGGESTION, BUT WAS RATHER SURPRISED TO FIND THE OTHER MEMBERS DISAGREED AND SAID IT WAS UNSUITABLE. HE WENT HOME SORROWING. TEN YEARS LATER THE SAME MAN WENT TO ANOTHER CONFERENCE. TO HIS SURPRISE THREE OTHER PEOPLE THERE MADE HIS SUGGESTION AND THE CONFERENCE ON THE WHOLE APPROVED AND DECIDED IT SHOULD BE TRIED. TEN YEARS LATER STILL THE SAME MAN WENT TO ANOTHER CONFERENCE AND THIS TIME HE HAD THE COURAGE TO OFFER HIS SUGGESTION OF TWENTY YEARS AGO HIMSELF. THE CHAIRMAN RULED IT OUT OF ORDER, SAYING "OH WE ARE ALL DOING THAT ALREADY". - MORAL: FOR SOME IMPORTANT CHANGES IN EDUCATION THE RELAXATION TIME IS TEN OR TWENTY YEARS.

Eric Rogers

THERMODYNAMICS FOR THE WHOLE SCHOOL POPULATION

Poul Thomsen

Royal Danish School of Educational Studies

Copenhagen

Professor George Marx has asked me to give a talk with the title: Thermodynamics for the Whole School Population.

As physics is usually only taught as a compulsory subject to students in the age group 13-16, I must try to suggest ways in which thermodynamics might be taught to youngsters of those ages, and as this seminar is called "Entropy in School" it is mainly the teaching of the second law I have to consider.

Let me first say that I believe the way we teach energy to youngsters to-day is not too bad. Many of us struggled hard for years to find ways of teaching energy in a better way than before. The way energy is taught differs, of course, from country to country, but in general the teaching is now mainly concerned with storage of energy and conservation of energy.

An important reason for teaching storage of energy is that in this way we may help to remove the mystery of the form of energy that everybody talks about and very few know much about: Nuclear energy or atomic energy, as it is usually called in newpapers - which makes the confusion even worse. A reason for teaching conservation of energy is that it makes it easy

to describe complicated events by referring to energy conversions.

I do not believe it is a good idea to change the introductory treatment of energy in order to teach the second law. We should rather try to find ways in which we can extend the treatment of energy to include aspects of the second law. How this can be done depends on the way the concept of energy has been introduced. It means that some sort of phenomenological approach might be adequate in some countries, whereas a statistical approach might be preferable in other countries. My own experience in teaching energy to all youngsters of the age group 13-16 comes from my engagement in the Danish physics chemistry project Ask Nature which was developed in the last half of the seventies. Therefore I find that the best way I can contribute to this seminar is by describing how the treatment of energy in the Ask Nature programme might be extended to include aspects of the second law.
In the Ask Nature programme the molecular structure of matter plays an important role, and a molecular model is used to make students understand how energy may be stored in gases, liquids and solids. In this case it is therefore natural to make use of a statistical approach.

The students learn that there only exist two main forms of energy: Kinetic energy and potential energy. All other forms of energy are regarded as names of different combinations of the two main forms. Energy conversions are illustrated by a number of simple experiments. As an example, let me indicate how the idea of conservation of energy is introduced. A trolley is placed on a slightly sloping runway to compensate for friction. As shown in fig. 1 the trolley is set in motion by means of the stretched

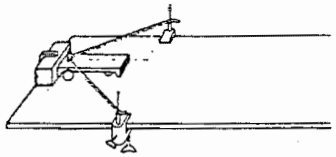


Fig. 1

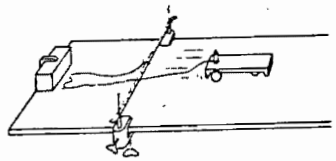


Fig. 2

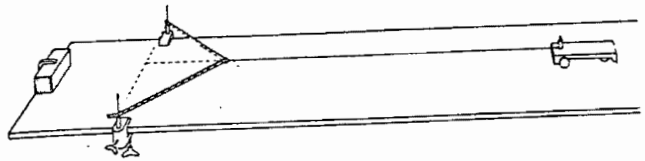


Fig. 3

rubberband. In fig. 2 the potential energy stored in the stretched rubberband is converted into kinetic energy for the moving trolley, and in fig. 3 the trolley has come to rest and the energy is again stored as potential energy in the stretched rubberband. It is found that the rubberband is stretched the same distance, when the trolley comes to rest (fig. 3), as it was before the trolley was released (fig. 1).

From this experiment it is concluded that potential energy can be converted into kinetic energy, and kinetic energy converted into potential energy without loss, if there is no friction.

Now the students investigate a large number of oscillating systems, and it is pointed out that in all the oscillating systems energy is stored, so that the energy continually changes between kinetic and potential energy. Again it is mentioned that the amount of

energy stored in the oscillating systems would be conserved if there was no friction.

This activity serves as an introduction to the concept of internal energy. The students are told that energy can be stored in a solid in the form of oscillations of the atoms or ions, of which the solid is composed, and the name internal energy is introduced. Finally, it is pointed out that friction just means that energy is converted into internal energy, and that this means that energy is always conserved in a closed system.

I shall not vaste time on describing how the concept of internal energy is extended to include liquids and gases. I just want to point out that this approach makes it easy for students to see that internal energy is not, in principle, different from nuclear energy . In fact, the only difference is that internal energy is concerned with the motion and interaction of molecules, atoms or ions, whereas nuclear energy is concerned with the motion and interaction of nucleons. That so much more energy is stored in heavy nuclei is explained by calling attention to the extremely short distances between the protons, which means that a large amount of energy is stored in the form of potential energy.

The concepts of work and heat are only used in connection with changes of the energy of a system. The term heat is mainly used in the form heating, and it is underlined that heating means exchange of energy between molecules.

It is explained how energy stored in different ways can be released and utilized in practice, but the concept of efficiency is not introduced. It is just described how various engines work, without any reference to the second law.

The Second Law

How might we extend the treatment to include something about the second law? I know there are physicists who claim that it is much

easier to make students understand the second law than the first law, but I disagree entirely. I admit that experiences from daily life have taught us to distinguish between events which could just as well happen in reverse and events which cannot, but it does not mean that it is easy to go from this to the concept of entropy. However, we might be able to go part of the way.

We could start by making the students aware of the fact that in many cases they are able to decide whether an event is shown forwards or backwards on a film. The three film loops "Forwards or Backwards" made for unit 9 "Change and Chance" in the Nuffield A-level project might be used for this purpose, and the Hungarian films on the same topic presented at this seminar would, of course, also be very useful. ("Crazy Stories" or "Furcsa történetek")

The next move is to explain by use of statistical arguments, why some experiments can <u>not</u> happen in reverse. To make this explanation easier to understand and more exciting we can let the students play the game shown in fig. 4. This game is inspired by a similar game in "Change and Chance" but the rules are not the same. As shown in the figure a few numbered chips (for example 4) are placed in the left half of a rectangle. The number

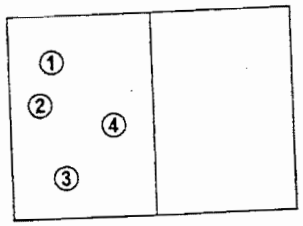


Fig. 4

of students participating in the game is the same as the number of chips. Each of them gets a die and a dice cup and is told which chip he is responsible for. Each participant casts a die at the

same time. If 1, 3 or 5 comes up, means that the chip in question is moving to the right. If 2, 4 or 6 comes up, means that the chip is moving to the left. If a chip is moving towards the middle of the rectangle, the player who takes care of this chip has to move it to the other half of the rectangle. The students count the number of casts they need before all the dice are again found in the left half of the rectangle.

When the students have played the game for some time they are asked to figure out, how many casts they would need on the average if they repeated the game a lot of times. Furthermore, they are asked to figure out, how often in $2^4 = 16$ casts they would expect that 1, 2, 3 or 4 chips would be in the left half of the rectangle.

The idea is to make them aware of the fact that the distribution with 2 dice in each half of the rectangle is the most probable. Finally, they are asked to consider what would happen if they played with a greater number of dice.

If the school is equipped with an air-table of the type, in which pucks can be kept in continual motion by an oscillating rail, experiments like the one shown in fig. 5 is a good alternative or supplement to the game described above.

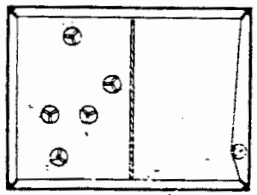


Fig. 5

At a certain time the wooden bar in the middle of the table is removed, so that the pucks can move around over the whole surface of the table. The students are asked to observe the random motion of the pucks and measure, how long time it takes, before all the pucks happen to be in the left half of the table again.

They might for example start with 3 pucks and gradually increase the number. They do not need to add many pucks before they lose their patience and declare, that they find it highly improbable that all the pucks should ever again be found in the 1 ft half of the table.

A Careful Look at the Filmed Experiments

We now go back to the filmed experiments and analyse the different events in the light of probability considerations. One of the experiments, shown in reverse, deals with mixing ink with water. Another experiment, also shown in reverse, illustrates what happens when a brick falls down on the floor.

The mixing of ink with water has many features in common with the game with the chips or the experiments with the pucks on the air-table, and it is therefore easy to explain why that event is not reversible. We might also draw attention to events from daily life which can be explained in a similar manner, for instance compressed air leaking out from a punctured bicycle tube, and we might point out that in a similar way we can explain why the molecules of a gas in a container will be evenly distributed over the enclosure. Furthermore we could do the experiment shown in fig. 6.

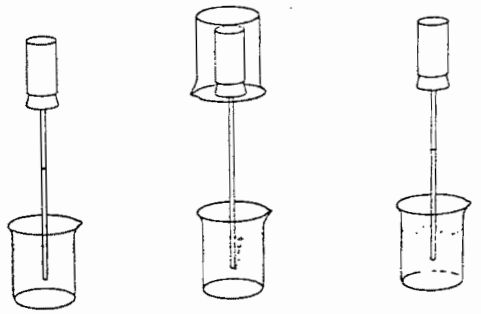


Fig. 6

Here the long glass tube, half filled with water, is connected with a porous clay cylinder by help of a rubber stopper, and the end of the glass tube is submerged in water (fig. 6a).

It is observed that the water surface in the glass tube slowly sinks down to the surface of the water in the beaker which proves that it is possible for the air molecules to penetrate the walls of the clay cylinder. Next a beaker filled with hydrogen is placed around the clay cylinder (fig. 6b), and it is seen that air now is bubling out of the glass tube. It proves that the hydrogen molecules are moving faster into the cylinder through the porous walls, than the air molecules are moving out, and it is pointed out that this is a consequence of the fact, that the average speed of the hydrogen molecules is larger than the average speed of the air molecules.

When the beaker around the cylinder is removed the water surface in the glass tube raises again, which indicates that the hydrogen molecules in the clay cylinder move faster out through the walls than the air molecules move in.

A careful discussion of this experiment will make students understand that the hydrogen molecules as well as the air molecules tend to be distributed uniformly on both sides of the walls of the porous cylinder, because they are behaving in a similar way as the chips in the game.

A discussion of the experiment with the falling brick is also very profitable. The students will intuitively understand that it is highly improbable that the brick dropped on the floor should suddenly jump up getting the necessary energy by reducing its own internal energy. This can be used as a starting point for a discussion of the role friction plays in daily life, and I believe that in this way we can make students realize that there seems to be a general tendency in nature to increase the amount of internal energy at the expense of other forms of energy.

Heat Conduction

So far we have drawn attention to one important aspect of the second law. However, students also need to realize that the internal energy tend to be distributed in such a way that all temperature differences disappear. It means that we also have to look at heat conduction.

As we are teaching physics to all youngsters we cannot make use of sophisticated theoretical models, but by doing the experiment shown in fig. 7, we can give the young people an idea of how the internal energy of a solid is distributed among the oscillating atoms or ions.

In fig. 7 the 16 magnet pendulums, arranged in a regular pattern, represent the atoms or ions. As seen in the figure the magnets

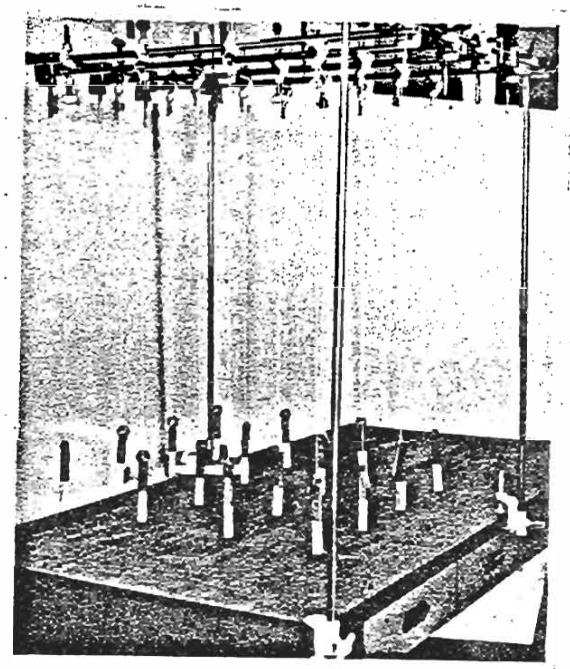


Fig. 7 (Photo: M.K. Aagaard)

are attached to the strings by help of iron nuts, so that they can be easily removed. A few magnets are set in oscillation, and it is observed that gradually the energy will be spread among all the magnets.

To illustrate heat conduction the 8 magnets in the right half of the pattern are kept at rest, and the magnets in the left half are set in oscillation. When the magnets in the right half are released it is seen that energy is transferred from the left (hot) half of the system to the right (cold) half. Again we can point out that the situation is similar to the situation in the game with the chips.

As students know that temperature is a measure of the motion (kinetic energy) of the molecules (atoms or ions), they conclude that a cold and a hot piece of the same material some time after they are brought into contact will assume the same temperature. That the same will happen if the two pieces consist of different materials is too difficult to explain theoretically. We can tell them, it is so, and point out that from daily life experiments they know very well that an object after some time assume the same temperature as the surroundings.

We have now come so far that we can express the second law qualitatively in the following way:

> It is a law of nature that the amount of internal energy will grow at the expense of energy stored in other ways. Furthermore, the internal energy will tend to be distributed in such a way that all temperature differences disappear.

Utilization of Energy

In the light of the second law we can now explain how we utilize energy sources in practice. We can begin by drawing attention to the fact that we are deliberately transforming other energy forms into internal energy when we burn oil, wood or coal in our furnaces. We point out that energy is not created when oil molecules and oxygen molecules react and form new molecules in the

burning process. What happens is only that the atoms of the original molecules are rearranged in such a way that more energy is stored as internal energy and, what is very important, in such a way that we achieve a high temperature.

We can then go on to investigate how we manage to make machines do work for us. As an example we might consider a petrol engine and explain how energy stored in the system of petrol and oxygen is converted into internal energy of the products of combustion. We point out that the temperature becomes very high and the pressure in the cylinder consequently very large. We describe how the high pressure forces the piston to move and point out that in this way we convert part of the internal energy of the hot gas into other energy forms. If, for example, the engine drives a car uphill, part of the energy is converted into potential energy. This leads to a discussion of car driving in the mountains, and we draw attention to the fact that the engine of a car climbing a steep mountain road sometimes becomes so hot that it is necessary to stop the car and let the engine cool. In this way we draw attention to the fact that a working engine always converts part of the energy fed into it into internal energy of the surroundings. We point out that this is a consequence of the general law the students have learnt and that this implies that, whenever we manage to make an engine do work for us, we have to pay duty by converting part of the energy into internal energy of the surroundings. This leads to the concept of efficiency.

I do not think it is possible to find convincing arguments for the fact that the maximum efficiency becomes higher when the temperature of the engine is increased, but the students should be told that it is so, and that the maximum efficiency is given by the expression

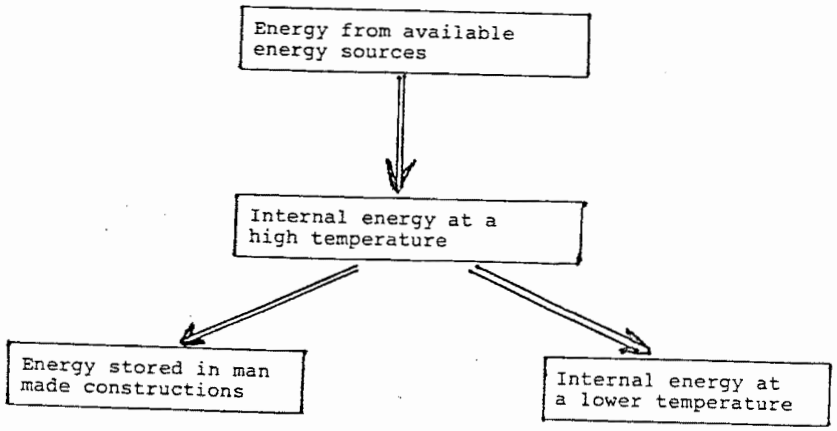
$$\eta = \frac{T_2 - T_1}{T_2} .$$

Finally we point out that it is possible to achieve a much higher efficiency if we avoid the connecting link of converting the stored energy into internal energy of a high temperature. As an example we might describe how the energy stored in an electric cell can be utilized to drive an electric motor.

Conservation of Energy and the Second Law

In our discussions it has been mentioned that it might be risky to teach students about energy conservation, because it might tempt them to believe that we do not need to worry about lack of energy. I believe that a treatment of the second law along the lines I have outlined above will eliminate this risk. We just have to point out that the expression "we use energy" only means that we convert energy in different forms into more or less useless internal energy.

It has also been mentioned that students might find it strange that flowers and trees grow up and form beautiful patterns. They might find that this is in contradiction to the second law. To prevent this misunderstanding we might underline that by the help of machines we can build houses, ships, cars and so on. As an example we might look more closely at the energy conversions when bricks are lifted from the ground to the top of a building by the help of a petrol engine. We point out that the energy originally stored in the system of petrol and oxygen is first converted into internal energy at a high temperature, and that only part of this energy is used to lift the bricks. The remaining part is converted into internal energy of lower temperature. It illustrates that in practice we often make use of the following chain of energy conversions:


Energy from available energy sources
Internal energy at a high temperature
Energy stored in man made constructions
Internal energy at a lower temperature

It means that the second law does not prevent us from making a lot of complex constructions, but we have to pay duty each time in the form of an increase of more or less useless internal energy.

Returning to the flowers and trees we now point out that the mechanisms which make living organisms grow are similar to the ones we make use of when we build man-made constructions. Therefore it is not strange that plants grow up, if only sufficient energy is available, and we may point out that we receive an enormous amount of energy from the sun each day. We might even go a little further and explain how the large energy quanta in the sunlight makes the photosynthesis possible.

When Time is Short

In most countries only a short time is assigned to the teaching of physics, and consequently only a limited time can be spent on each of the many topics in the syllabus. It is therefore questionable if it will be possible to stretch the time used to teach energy so much that the second law could be treated in the way I have outlined. If not, it might be an idea to tell a story of the ways in which mankind has learned to utilize various kinds of energy sources. In the story we point out that energy resources may be regarded as invisible springs, some of them rather weak, others very strong. We continue by giving a vivid discription of how human beings gradually discovered more and more springs and learned to release the energy stored in them (discovery of fire, invention of gunpowder, release of nuclear energy). In this way I believe the students receive the intuitive impression that something irreparable happens when the springs are released, and this is, as we know, the main content of the second law.

SOME IDEAS FOR DEALING WITH ENERGY DEGRADATION IN GRADES 5 TO 10

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The following ideas are based on a teaching module on energy degradation, we developed during a seminar on lesson planning in cooperation with teacher students. Unfortunately, our proposals have not been tested in school yet. We hope to do this in the near future.

1. SOME REMARKS ON THE SIGNIFICANCE OF ENERGY DEGRADATION FOR PHYSICS TEACHING

There is no doubt that energy supply is an important topic of physics instruction in grades 5 to 10. Members of syllabus committees, textbook authors, teachers and other people being involved in physics instruction are in agreement regarding the significance of this topic. An empirical study dealing with aims of physics education has corroberated this recently (see HÄUSSLER et al., 1980).
Although there is an agreement concerning the importance of this topic, there is a great number of difficulties with regard to teaching this aspect in school practice. Doubtless the energy concept was given more attention in grades 5 to 10 during the past 10 years. But it may be questioned whether physics instruction - as it is given in most of our schools -

is indeed able to provide students with conceptions of energy which facilitate an understanding of energy problems in society. A study on the role of the energy concept in school has led, besides others, to the following hypothesis: the energy concept gained by students in physics instruction which follows mainly traditional paths[1] is not able to aid an understanding of energy problems (see DUIT, 1983). This is true especially because energy degradation is not at all contained in physics teaching of this age level or given only little attention.

It is not possible within this paper to discuss in detail which aspects of the energy concept may provide aids for understanding problems of energy supply. Only some remarks can be given (see for further details DUIT, 1983).
It seems to be no doubt that the conceptualisation of energy is of influence on the mentioned understanding. If energy is conceptualized as an abstract quantity which balances processes only little help will be gained for understanding problems of energy supply. A conceptualisation being closer to the meaning of energy in everyday language seems to be more adequate. Such conceptualisation has been proposed, for instance, by ROGERS (1965).
It seems to be obvious that the aspects of energy transfer and energy conversion are necessary. As the aspect of energy conservation is concerned, it has been brought into prominence that this aspect may hamper an understanding of energy problems. The students may ask why there is a problem of sufficient energy supply when energy is conserved (see e.g. SCHLICHTING, BACKHAUS, 1980; OGBORN, 1981; DUIT, 1981b; SOLOMON, 1982). The aspect of energy degradation is much more important here. To get an understanding of energy problems in society seems to be unlikely without any insight in this aspect.

1 The teaching of energy in most of our schools still follows mainly the traditional path via force and work. Of course, the limitations of this path are lowered by introducing not only mechanical energy forms but also energy forms from other areas of physics. Furthermore, the aspects of energy transfer, energy conversion and energy conservation is given attention. Notwithstanding this, quite often force and work still are taking much more time in physics instruction than energy.

Aims and teaching seem to be in contradiction with regard to problems of energy supply. Physics instruction in most of our schools prefers a conceptualisation of energy (energy is the ability to do work or the like) which does not fit sufficiently with the aims. Furthermore, it deals in some detail with an aspect (energy conservation) which may hamper an understanding whereas the most important aspect with regard to the aims is given almost no attention.

2. SOME IDEAS ON TEACHING ENERGY IN GRADES 5 TO 10

Before dealing with the aspect of energy degradation more in detail we want to outline very briefly some ideas of teaching energy in grades 5 to 10 (see DUIT, 1983).

Energy should be introduced early in this age level to provide a basis for dealing with energy in biology, chemistry and social studies, too.
The meaning of energy in everyday language serves as starting point. Energy is introduced as a general kind of fuel. Energy is needed to set something in motion, to lift up something, to light up a bulb, to heat up bodies etc. In general, energy is a precondition to run processes in nature and technology. It has to be stressed that energy is not solely a luxury item (i.e. something needed to make our lives more comfortable) but a precondition for our lives in general.
The concept of work is superfluous when introducing energy. In general, this concept is not needed in the path to the energy concept outlined here.

Right from the start the aspects of energy transfer and conversion are given attention. Energy is conceptualized as something that can be stored and transported. The following analogy may be of profit in order to stress the fact that in all energy changes energy still remains energy: when energy is converted from one form to the other there is only a change of the dress energy wears.

With regard to the aim of aiding an understanding of energy problems, the following idea of energy conservation seems to be sufficient: there is no loss and no gain of energy. Energy cannot be created and energy cannot be destroyed. Dealing with this aspect in a more formal and quantitative manner (including, for instance, processes of frictionless mechanics) seems to be superfluous with regard to the stated aim.[1]

The aspect of energy degradation can be regarded from the very beginning of teaching about energy. When dealing with energy conversion and transfer, for instance, it is easy to point out that the energy cannot be used another time to run the same process once more. We still have energy, but the energy is of lower use. Further ideas of dealing with this aspect are presented in the following section.

3. ENERGY DEGRADATION IN GRADES 5 to 10

Fig. 1 presents the structure of our proposals for dealing with energy degradation in grades 5 to 10. Although the blocks of fig.1 outline teaching activities the wording is meant for the expert (e.g. the teacher) not for the student.

The ideas presented here, have been stimulated by approaches already published. We try to integrate proposals which do not give an interpretation in the particle model (e.g. SCHLICHTING, BACKHAUS, 1980) with approaches based on the particle model (e.g. HABER-SCHAIM, 1981).

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1 To avoid misunderstandings, it seems to be necessary to mention the following. There are, of course, good reasons for dealing with the aspect of energy conservation in a quantitative manner. But such teaching activities are done in the interest of other aims than that presupposed here. Another aspect has to be regarded. Empirical studies point out that students in grades 5 to 10 have severe difficulties to apply the principle of energy conservation when explaining processes of (frictionless) mechanics (see e.g. DUIT, 1981a, 1983).

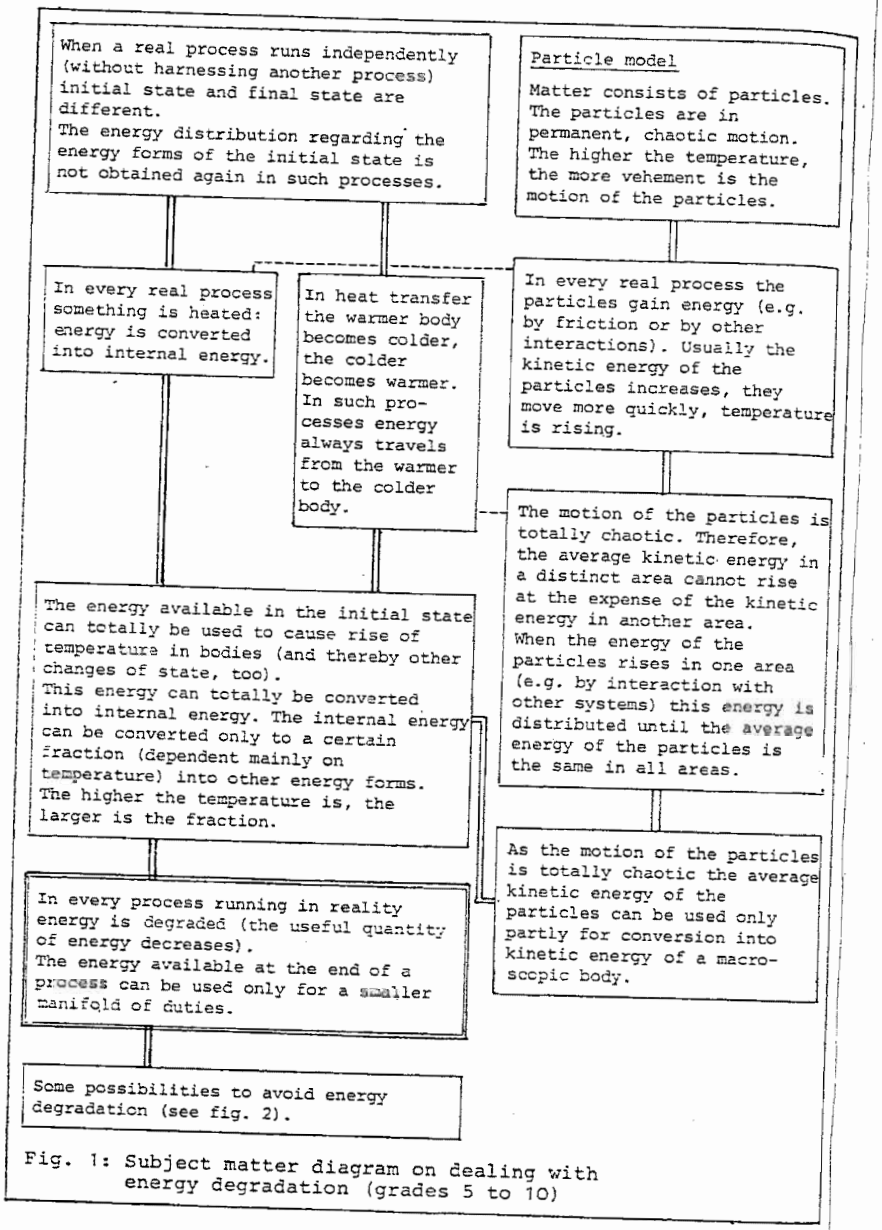
When a real process runs independently (without harnessing another process) initial state and final state are different.
The energy distribution regarding the energy forms of the initial state is not obtained again in such processes.
Particle model
Matter consists of particles. The particles are in permanent, chaotic motion. The higher the temperature, the more vehement is the motion of the particles.
In every real process something is heated: energy is converted into internal energy.
In heat transfer the warmer body becomes colder, the colder becomes warmer. In such processes energy always travels from the warmer to the colder body.
In every real process the particles gain energy (e.g. by friction or by other interactions). Usually the kinetic energy of the particles increases, they move more quickly, temperature is rising.
The motion of the particles is totally chaotic. Therefore, the average kinetic energy in a distinct area cannot rise at the expense of the kinetic energy in another area.
When the energy of the particles rises in one area (e.g. by interaction with other systems) this energy is distributed until the average energy of the particles is the same in all areas.
The energy available in the initial state can totally be used to cause rise of temperature in bodies (and thereby other changes of state, too).
This energy can totally be converted into internal energy. The internal energy can be converted only to a certain fraction (dependent mainly on temperature) into other energy forms.
The higher the temperature is, the larger is the fraction.
As the motion of the particles is totally chaotic the average kinetic energy of the particles can be used only partly for conversion into kinetic energy of a macroscopic body.
In every process running in reality energy is degraded (the useful quantity of energy decreases).
The energy available at the end of a process can be used only for a smaller manifold of duties.
Some possibilities to avoid energy degradation (see fig. 2).

Fig. 1: Subject matter diagram on dealing with energy degradation (grades 5 to 10)

It is not necessary to discuss the aspect of energy degradation here from the physics point of view (see e.g. FALK, RUPPEL, 1976, 281; FALK, 1979; RANG, 1981; BACKHAUS, SCHLICHTING, 1981a, b).
Our proposals are based on the following version of the second law of thermodynamics:

- In every process running in reality the energy of the initial state is partly converted into internal energy.
- In heat transfer energy always travels from the warmer to the colder system.
- Internal energy can be converted into other energy forms (by a machine working cyclic) only to a distinct extent which is dependend on temperature.

The left side of the diagram presented in fig. 1 contains the core of our proposals. The right side contains enrichments of understanding employing the particle model.
We start with processes in nature and technology familiar to the students. We observe that the same state is not gained again by systems which run independently (without harnessing another process). Newton's apple always falls to the earth, the initial height is not gained again. If one wants to bring a system back to the initial state one has to use other processes (e.g. lifting by using a motor): energy wears other dresses at the end of every process running in the real world than in the beginning.

We then pay attention to heat. In every real process something is heated up. In processes of heat transfer the warmer system becomes colder, the colder warmer. We do not use the term heat energy here in order to avoid misconceptions on heat (e.g. heat is not stored in s system).

Whereas the content of the blocks mentioned so far is based on everyday experiences of the students, this is true only partly for the following block. What we know already is the fact that in every process heat plays an important role. It seems to be easy to convince the students that it is possible

to use every available energy totally to heat up something. Some problems arise only when changes of state like boiling occur, when energy is "used up" although the temperature is constant. Therefore, we point out that energy can be converted totally into internal energy. The particle model may be employed to enrich the understanding of this aspect.
The most difficult point of dealing with energy degradation is the fact that internal energy can be converted only to a certain fraction into other energy forms. The particle model provides helpful arguments here. The wording in the last block on the right side of the diagram in fig. 1 outlines only a minimum level of understanding. But it may convince the students. As soon as we go into more details the explanations in the particle model become more complicated so that probably not all students in grades 5 to 10 will be able to follow.

In the last block on the left side, we mention some possibilities to reduce energy degradation. We prepared information materials for these possibilities in order to facilitate group work in class. Fig. 2 presents a worksheet summarizing these possibilities of energy degradation for the students.

4. CONCLUDING REMARKS

The proposals on dealing with energy degradation presented in section 3 outline a programm for the whole school level regarded here (grades 5 to 10). Teaching energy, in general, is not a task which can be executed in only one attack. Several attemps within a spiral curriculum have to build up the conception of energy (including the conception of energy degradation) step by step. Our ideas seem to fit best into teaching about energy as outlined in section 2. But they may be partly realized in other approaches, too.

SOME POSSIBILITIES TO REDUCE ENERGY DEGRADATION

In every process energy is conserved (there is neither an energy gain nor an energy loss) but the use of energy is decreasing ...

because the initial energy (e.g. electrical energy) is partly converted into internal energy. Internal energy cannot be totally converted in other energy forms (e.g. electrical energy).

because the initial energy if it is already internal energy is converted to internal energy of lower temperature (which is of less use).

In order to reduce energy degradation there are, for instance, the following possibilities:

1. Possibility

To take care that in a process as less energy as possible is "used up" for heating something. In order to brake a car, for instance, the surplus of kinetic energy can be converted into electric energy (using a generator) instead of using up the energy by friction.

2. Possibility

To use unavoidable heat losses otherwise. Examples: Use of the heat loss of powerplants to heat up houses or fishponds.

3. Possibility

To use insulations in order to keep the energy where we need it. Examples: thermos flasks / heat insulation of the house.

4. Possibility

To take care of minimum heat losses by employing the counterflow principle. When changing the warm (but used up) air in living rooms for cold fresh air, one can use a tube with two walls. The warm air going out, heats up the cold air coming in.

Please think about the mentioned possibilities to reduce energy degradation. Please try to find further examples!

Fig. 2: Draft of a worksheet summarizing some aspects of energy degradation.

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"ENERGY? WHAT COULD IT BE?"

"L'ENERGY, C'EST QUOI?" UNE NOU PUBLIC

Louis Timbal-Duclaux

Information and Communication Division

Department of Equipment, Electricité de France

1) QUI ? : LES AUTEURS

La plaquette que nous vous présentons résulte d'un travail d'équipe de 4 personnes ; les deux premières appartenant à E.D.F., les deux autres à un cabinet extérieur :

- un spécialiste des problèmes d'économie de l'énergie, Jacques LACOSTE : il a apporté la méthodologie et les concepts de base ;
- un praticien des problèmes de communication écrite, Louis TIMBAL-DUCLAUX, qui, d'une part s'est efforcé de traduire la pensée du précédent de manière plus accessible pour le public, et qui, d'autre part, a suivi et supervisé la réalisation de la plaquette ;
- un spécialiste de la communication, Jean-Michel BOURDIER, du cabinet "Image et Signe" ; il a vérifié, d'une part que le "message" des deux premiers était effectivement compréhensible par le public ; de l'autre, il s'est chargé de la réalisation matérielle de la plaquette ;
- un illustrateur, Frank JACKSON, sélectionné par le précédent, qui a traduit fidèlement en dessins, le message, dans le style d'humour bon enfant qui lui est propre.

2) QUOI ? : LA PLAQUETTE

C'est par un va et vient permanent entre ces quatres personnes que la plaquette s'est progressivement élaborée au cours de l'année 1981.

Un premier tirage de 20.000 exemplaires a été épuisé en moins de 9 mois, par une distribution à l'intérieur d'E.D.F. réalisée uniquement à la demande.

A la suite de certaines remarques critiques des lecteurs et utilisateurs de la plaquette, des corrections ont été décidées pour la 2ème édition. Elles touchent uniquement la dernière partie, à savoir : système énergétique.

Au départ, les auteurs avaient prévu la réalisation d'un tome II, consacré aux applications, à paraitre à la fin 1982. Ils ont finalement renoncé à le faire, partie par manque de temps, partie parce qu'ils sont arrivés à la conclusion que si les principes du tome I avaient été bien assimilés, les lecteurs n'auraient pas de mal à les appliquer eux-mêmes à une situation énergétique précise, compte-tenu des suppléments d'information contenus dans la 2ème édition.

3 UNE DOUBLE NOUVEAUTE

Comme le lecteur s'en apercevra, cette plaquette présente une double nouveauté : de fond et de forme.

- De fond : c'est la première fois, à notre connaissance, que le problème général de l'énergie est abordé directement avec les concepts de la pensée économique (nous y reviendrons).

- De forme : c'est aussi une tentative de réalisation d'un message qui soit, dès le départ, multi-média.

La plaquette comporte déjà en effet un double circuit de lecture : d'une part un texte qui, seul, est auto-suffisant ; de l'autre un nombre égal de planches illustrées, qui constitue à la fois un circuit de lecture rapide et un support directement utilisable pour la rétroprojection.

De plus, cette série de planches est utilisable - moyennant des adaptations mineures - pour réaliser d'autres supports de communication : diapositives, panneaux d'exposition, films, etc...

De fait, un film d'animation sur ce sujet est actuellement à l'étude film qui pourra être diffusé par la suite soit par le cinéma, soit en bandes vidéo.

4 POUR QUI ? : LE PUBLIC VISE

A qui s'adresse cette plaquette ? A un large public. Il s'agit en effet d'un travail de vulgarisation scientifique et technique.

Mais qu'on ne s'y méprenne pas : sous des dehors plaisants cette plaquette demande en effet au lecteur attentif d'abandonner la vision superficielle qu'il avait des problèmes énergétiques pour la changer en une compréhension plus approfondie. De passer d'une vision "chosiste" d'un catalogue de sources d'énergie à une vision relationnelle où l'énergie devient une vaste dialectique entre un ensemble de sources et un ensemble d'usages, au sein d'un système global fait de chaînes énergétiques entrecroisés d'une grande complexité.

Au départ, les auteurs cherchaient à toucher un public interne à EDF : formateurs, conférenciers, attachés de relations publiques et autres hommes de communication. De fait, de par son caractère plaisant, la brochure a été vite demandée par des cercles beaucoup plus vastes : cadres et agents de maîtrise, sinon personnel d'exécution. De plus, par publicité de bouche à oreille, la plaquette a été diffusée à l'extérieur d'EDF, notamment dans le milieu scolaire et universitaire.

Un certain nombre de personnes ont pris la peine de nous écrire, et ce sont leurs encouragements, joints à l'épuisement rapide de la première édition, qui nous ont amené à nous remettre au travail pour publier la nouvelle version revue et augmentée.

II POURQUOI CETTE PLAQUETTE ?

Situation. Dans les années 1950-1970, l'abondance pétrolière avait relégué au dernier plan les problèmes énergétiques à tel point qu'un ministre de l'industrie de l'époque pouvait déclarer sans honte "moi, quand j'étais au gouvernement, l'énergie j'ai toujours fait l'impasse dessus !" De fait, pourquoi se préoccuper d'une question quand tout va bien et qu'il n'y a pas de problème ? A cette époque, seuls les experts des organismes et entreprises énergétiques se préoccupaient de l'énergie : c'était un sujet technique parmi cent autres.

A partir de 1970, une poignée d'experts du Plan tira la sonnette d'alarme en posant la question "abondance pétrolière, jusqu'à quand ?". Mais il fallut attendre en 1973 la guerre du Kippour, puis en 1974 le lancement du programme nucléaire, pour que les journaux et le public commencent à agiter ces questions.

Dès lors, au cours de la décennie 1970, il n'y eut guère de mois, voire de semaine, sans que les nouvelles touchant à l'énergie ne fasse l'objet de gros titres des journaux. Face à la crise, les acteurs sociaux prirent position : partis politiques, syndicats, associations, entreprises, ministères, gouvernements, organismes internationaux, comités d'experts... Bref, si dans la décennie précédente on n'avait pas assez parlé de l'énergie, maintenant on n'en parlait trop et souvent mal. Abasourdi par une avalanche de nouvelles souvent contradictoires, le public se demandait qui croire et que croire.

Problème. De par la réalisation du programme nucléaire à eau sous pression, EDF, se trouva soudain projeté au coeur de l'actualité et du débat. Attaqué parfois violemment par certaines associations écologistes ou politiques, défendu par d'autres, il fut sommé de répondre aux questions de la presse et du public et de justifier la politique énergétique qui avait été décidée par les pouvoirs publics.

Ce fut l'époque du "débat nucléaire". Mais dans le terme "énergie nucléaire", il y a deux mots énergie et nucléaire.

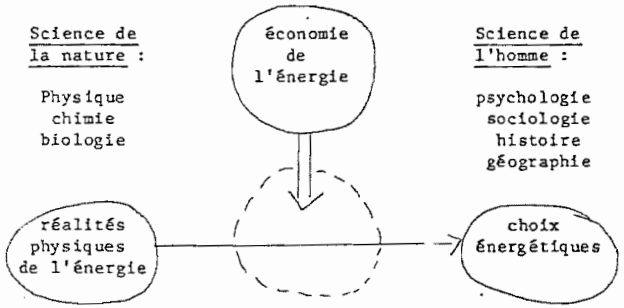
A travers un débat axé au départ sur les coûts, les avantages et les risques du programme nucléaire, c'était en fait la question fondamentale des choix énergétiques qui était posée, certains opposant en effet au "mauvais" programme nucléaire, un "bon" programme fondé sur les économies d'énergie et les énergies dites "douces" parées de toutes les vertus : non polluantes, décentralisatrices, gratuites...

LE CHAINON MANQUANT

Bref, ce débat, qualifié de nucléaire, était en fait énergétique. Et tous les jours de nouvelles preuves nous montraient que tant que nous ne disposerions pas d'une méthode commune pour évaluer les apports respectifs des énergies classiques, des énergies dites nouvelles et de l'énergie nucléaire, ce débat continuerait en bonne partie à se présenter comme un dialogue de sourds fondé plus sur des présupposés idéologiques que sur un examen des réalités.

Nous étions en particulier, assez choqués de voir comment certains, plaquant brutalement des notions tirées de la physique aux choix politiques, aboutissaient à de véritables contre-sens. Cela notamment pour des notions comme celle de "rendement" ou d'"énergie utile" qui, employées hors de leur contexte initial de la physique, peuvent induire largement en erreur un public même averti.

En bref, plaquer directement le domaine des sciences physiques sur celui de la socio-politique sans respecter les indispensables médiations, nous paraissait une erreur méthodologique majeure. De fait, c'était négliger les apports de la pensée économique qui se situe entre ces deux pôles, à mi-chemin entre les sciences de la matière et celles de l'homme.



Pour ne prendre qu'un seul exemple, comment ne pas voir la contradiction flagrante entre la première loi de la thermodynamique : "l'énergie se conserve toujours" et les campagnes des gouvernements et des associations : "économisez l'énergie !". De fait, dans l'un et l'autre cas on ne se situe pas dans le même cadre de référence et le mot "énergie" ne recouvre pas les mêmes réalités.

Résolution : une théorie générale de l'énergie fondée sur la pensée économique

De fait, seule une approche économique globale de l'énergie permet de résoudre le dilemme de l'énergie qui à la fois se conserve et ne se conserve pas et, plus généralement, le problème politique des choix énergétiques.

Le public raisonne en termes de quantité d'énergie c'est-à-dire d'abondance des sources (réserves et épuisement possible de telle ou telle source). Nous voulions lui montrer qu'il était autant, sinon plus important de considérer la qualité des différentes énergies, c'est-à-dire mettre l'accent sur la seconde loi de la thermodynamique, celle de Carnot. Cette qualité tient de fait à deux facteurs.

- sa densité (énergie incluse dans un certain volume de matière),

- son caractère plus ou moins ordonné : toutes choses égales par ailleurs une énergie ordonnée vaut plus qu'une autre moins ordonnée : par exemple l'énergie mécanique vaut plus que la chaleur.

De ce fait, il ne faut pas confondre énergie brute et énergie efficace. Il n'y a pas d'énergie efficace sans équipements. C'est-à-dire sans investissements, coûts d'exploitation et ce qu'on appelle péjorativement des pertes et qui sont en fait, la contrepartie de l'amélioration de qualité des énergies brutes. L'histoire de l'énergie, c'est en fait l'histoire des innovations technologiques qui ont permis de mettre les énergies brutes au travail. Cela, de la conquête du feu aux vols spatiaux.

III LA METHODE PEDAGOGIQUE ET LE PLAN RETENU

Préambule. Pourquoi il est normal que le lecteur soit moins au courant des problèmes énergétiques qu'il ne croie : parce qu'il en a une vision trop morcelée. Cette plaquette propose de rassembler ces fragments en une théorie cohérente.

Introduction : le paradoxe énergétique. D'une part le monde regorge d'énergie. De l'autre il en manque. La preuve : la crise actuelle du pétrole. Mais les crises énergétiques ne sont pas nouvelles, elles sont en fait aussi vieilles que le monde. Préhistoire : la guerre du feu. Antiquité, esclavage. Temps modernes : la grande crise du bois du 17ème siècle en Angleterre. De fait si l'énergie "sauvage" est super-abondante, l'énergie "domestiquée" l'est beaucoup moins. Car tout le problème énergétique, c'est de passer de l'une à l'autre.

I Pas d'énergie efficace sans convertisseur

Ainsi, entre la source et sauvage et l'usage, s'intercalent des machines, les "convertisseurs", fruits du travail humain. Exemple du chauffage au bois d'où l'on tire la notion de chaîne énergétique.

II Les chaînes énergétiques

Ces convertisseurs ont un triple rôle :
- vaincre les contraintes de lieu (transport), de temps (stockage), de qualité (mise en forme adéquate pour l'usage).

- Ils s'articlent en 4 stades de la source à l'usage : captation-collecte, transport-distribution, transformation, utilisation.

- Dans tous les cas, ce que la nature n'a pas fait l'homme doit le faire. Plus une source est dense et stockée, plus elle est facilement utilisable... mais alors elle n'est pas renouvelable. On n'a rien sans rien.

III Le système énergétique (nouvelle version)

Il est formé par l'entrecroisement des chaînes énergétiques et devient alors extrêmement complexe. Pour comprendre ses mécanismes, il faut distinguer 4 types principaux de relations entre sources et usages.

Deux situations de concurrence :

- une source dessert plusieurs usages ;
- plusieurs sources desservent un seul usage.

Deux situations de complémentarité :

- deux chaînes énergétiques entre la même source et le même usage ;
- deux ou plusieurs énergies (ensemble ou en alternance) pour desservir le même usage (systèmes multi-énergies).

- Une illusion : croire qu'il suffit de choisir cas par cas la "meilleure" source pour chaque usage pour résoudre le problème énergétique global. Une somme d'optimisations partielles ne fait pas une optimisateur totale du système énergétique. Il n'y a pas que le coût de la source qui compte, il y a celui des convertisseurs - notamment finaux, qui pèsent très lourd dans le bilan. Morceler à l'excès les chaînes énergétiques reviennent à augmenter, en fait, le coût total par le biais des investissements nécessaires.

- A l'inverse : plus le système énergétique réalisera une interconnexion poussée entre ses différentes chaînes, et plus son optimisation sera possible. La véritable solution consiste donc à "libérer les échanges" entre sources et usages pour améliorer la transparence du marché énergétique et augmenter les possibilités de choix, au moindre coût, à la fois des utilisateurs et des décideurs.

- De fait, malgré leur importance, les questions énergétiques ne doivent pas être érigées en absolu. L'énergie n'est qu'un facteur de production parmi les autres : capital, travail, matières premières, temps...
L'arbitrage politique doit se fonder, pour chaque acteur énergétique, sur un arbitrage économique. Toutes les situations énergétiques ne sont pas identiques, loin de là. Le cas français : réduire les importations de pétrole est prioritaire.

Conclusion. Pour traiter un problème énergétique il faut poser 5 questions :

- Combien ? nature et abondance de la source.
- A quel court ? coût des convertisseurs nécessaires.
- En combien de temps ? délais nécessaires, souvent longs.
- Avec quelles conséquences sur la nature et l'homme ?
- Et par quels chemins ? le choix des chaînes énergétiques les plus efficaces.

...

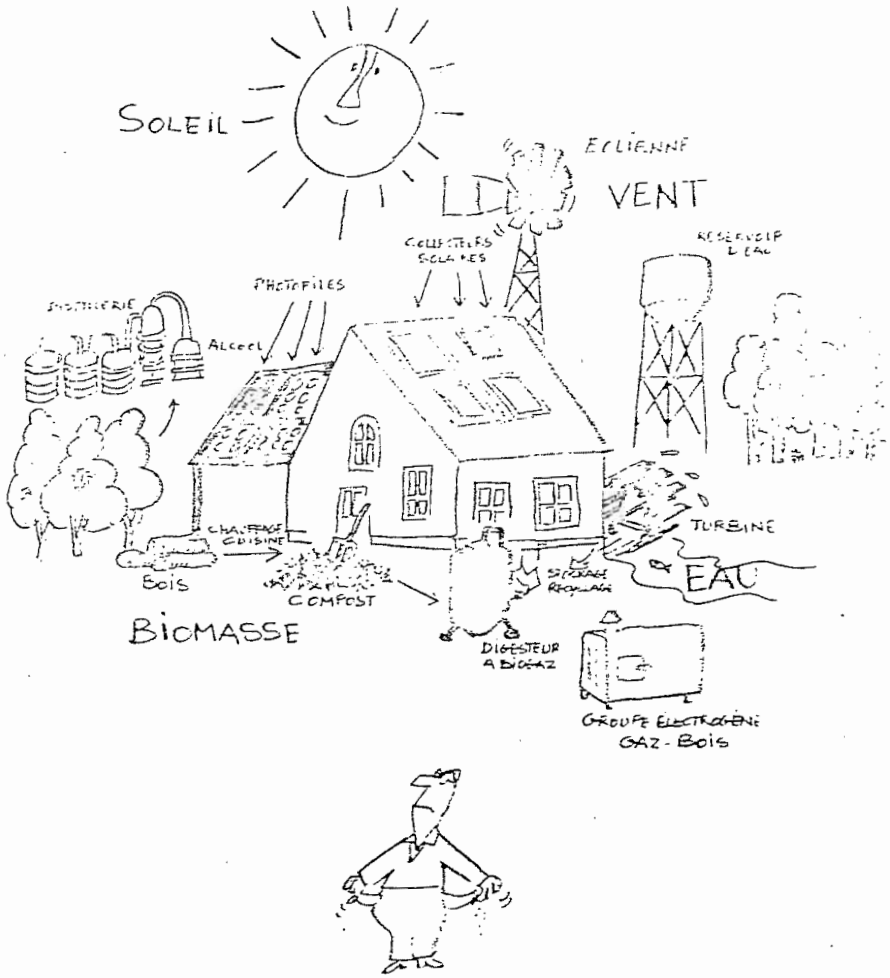
En résumé, nous estimerons que cette plaquette aura atteint son but si son lecteur, l'ayant lue et étudiée, non seulement à l'impression réelle d'en "savoir plus" sur l'énergie; mais encore et surtout a assimilé le petit nombre de concepts-clés qui lui permettront de réfléchir sur les nouvelles énergétiques qu'il reçoit chaque jour par la presse :

- Concept de source et d'usage énergétiques.
- Concept de convertisseur.
- Concept de chaîne énergétique.
- Concept de système énergétique.
- Concept d'optimisation économique d'une situation énergétique.

Bref, s'il devient désormais apte à monter, démonter, et faire fonctionner tout problème énergétique concret.

La maison "solaire" autonome

from "L'energie ... c'est quoi?"
by L. Timbal-Duclaux



ENERGY AND QUALITY

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Do we ever run out of energy ?
Well, yes we do, we run out of coal and oil, but not out of electricity.
Why not ?
Because electricity, that can be generated

Bart Lijnse, 11 yrs.

1. INTRODUCTION

Let me first apologize for being here, as I have not much to say about 'entropy', the topic of this conference.
In the Netherlands until now entropy has no place in the official physics curriculum. Not even in the physics curriculum for our most academic schooltype.
Therefore my talk will deal with the future; that is to say with one of many possible futures, and not with the present.
However, due to the efforts of the PLON-project, the Dutch Curriculum Development Project for Physics, we hope to be able to foster one possible future in particular !
As a part-time member of this curriculum team I am cooperating in the development of a new teaching unit, on: Energy and Quality, in which some rudimentary aspects of the entropy concept are dealt with. So, that's the reason why:
It's about this unit that I'ld like to report here.
My talk will be divided roughly in the following sections:
- some remarks about 'boundary conditions';
- a rough sketch of our pedagogical position;
- a description of the unit and its background.

2. BOUNDARY CONDITIONS

To be able to judge a newly developed teaching product one has to know something about the public for which it is meant. About their age and interests; their intellectual abilities and future occupational perspectives. About their relevant pre-knowledge, the available teaching time, the pedagogical climate they are used to and the characteristics of their socio-cultural environment and background, etc. All this has to be taken into account and it will be clear that I can't tell you now enough about it. So, just a few words, which seem to be the most relevant for the rest of my talk.

Our unit is meant for pupils in the age range between 16 and 18, depending on their schooling history.
They are <u>not</u> in the top of the ability range but somewhere between the sixtieth and eightieth percentile.
We are talking about a schooltype which is meant for higher <u>general</u> education and not for <u>pre-university</u> education. So, the occupational future of our pupils is not at the academic level, but at middle-level technical and business jobs.
The attitudes of those pupils are of a rather pragmatic nature. For them schooling is not so much an intellectual adventure as well as an occasion to learn something which has to be useful for some preferably nearby purpose. It is more a question of learning how than of learning why. The relevant

physical pre-knowledge and previous educational experiences of the pupils I'm talking about, may be very diverse. This has to do with one of the peculiarities of our school system.
On the other hand all of them have chosen physics as a subject for their final examination. However, many of them not because of pure interest in physics, but because the subject is considered to be a prerequisite for many possible future jobs.

As we are talking about energy-teaching a quite different but very relevant boundary condition is the socio-political background and knowledge of our pupils. As is well-known, Holland belongs to the rich industrialized western, capitalist countries, with an open democtratic social system.
Also well-known is the fact that we suffer from a rather severe economic crisis, which has everything to do with energy-prices and energy-policy.
Many people seek the solution for this crisis in a new economic-industrial recovery, initiated by new scientific and technological research, accompanied by large-scale energy-supplies and a growth of energy-consumption, among which the use of nuclear energy.
Others however seek the solution in a new personal style of living, small scale energy-supplies, nature-friendly, renewable technology, etc. and great emphasis on ever-lasting energy-resources and energy-savings.

Within this context, the energy-policy has become a key-factor for our future society and it has become a crucial example for the quality of our democratic decision-making. For instance, our government has made the decision on our energy-policy the main-issue of a large-scale public enquiry and debate. Participation is asked from as many citizens as possible in deciding about their own energy-future and thus about their own future quality of life.

It is within this social context that we teach about Energy. We have six weeks for our unit, i.e. 24 physics lessons. So, what to expect from such a short period of time for such a complicated topic ?
Has physics teaching really a role to play at all with regard to the social energy-problem ?

3. PEDAGOGICAL POSITION

<u>Classroom climate</u>
Of course, boundary conditions are only real boundary conditions if they are felt and accepted as such.
The fact that I have sketched them so extensively indicates that we do and that we try to take them seriously in our curriculum development.
So we think that in the actual teaching situation, differentiation is necessary, not so much according to ability (for our group of pupils) as well as according to pupils' interests, and learning styles.
We also have the opinion that so-called social teaching and learning should play an important role in the classroom. Therefore we plan deliberately much occasion for small group work and discussion.
Pupils have to report to each other about their sometimes very diverse activities, and are thus expected to learn as well from each other as from the teacher, etc. (for further characteristics and research results on 'open education', see Fraser 1983).
In short our general pedagogical philosophy is directed towards a growth in

both personal and social independence and responsibility. I agree, a rather pretentious goal to aim at. A goal which by definition will never be reached but that nevertheless serves as a valuable guiding principle in our work (Lijnse, 1981).

Curriculum-concept

However, where does this leave us, as far as curriculum-contents are concerned ?
In the usual 'structure-of-discipline' type of curriculum the structure of physics as a science serves as a relatively secure frame of reference for the choice of curriculum content. One tries to teach then what are considered to be the most fundamental concepts and rules of physics, as these are thought to be the most generally applicable, and therefore the most useful and valuable. So, one could say, it concerns what is regarded as the most general body of organised knowledge, as a safeguard against too much disconnected limitedly useful knowledge of facts.
From this perspective it is for instance quite understandable that one includes the concepts of energy and entropy and the first and second law into the school curriculum. The more so while the actual teaching-climate, related to a 'structure-of-discipline' curriculum is usually of a rather intellectual and scientific nature.
However, to our opinion this type of curriculum stems from a one-sided academic picture of physics. It overvaluates the role of academic physics, compared to technological and social physics. Apart from the fact that academic physics may be the closest to the world of 'pure' physicists, it certainly is also the farthest from the world of our pupils.
All this taken together, we have come to the conclusion that for our group of pupils, the structure of physics is no longer the only exclusive argument and sole reference-frame for the choice of curriculum content.
Instead, we think that what we teach about, be it concepts, skills or attitudes, has also to be really relevant for the world of pupils. Instead of explaining nature intellectually within the classroom walls only, we want our teaching to function in real-life situations that pupils encounter outside school (Broudy, 1977).
One could say that we have replaced the key-words: structure and generality, by two others: relevance and functionality.
This is the main reason why we have chosen to structure our curriculum thematically, i.e. in teaching units which deal with topics that are recognisable for pupils and which provide the possibility of teaching about relevant real-life situations.
This means that we sacrifice deliberatily 'generality of knowledge' in favour of 'functionality of knowledge'.
A 'loss of generality' in that respect that we teach concepts and rules of physics only within a certain thematic context. Therefore we cannot simply expect that such concepts can also be used in quite different situations (however, what about the success of teaching general knowledge in this respect ?).
But a 'gain in functionality' as we hope that our teaching does function indeed in the recognisable situations outside school.

Life world context

Now leaving aside the structure of physics as a main reference frame certainly makes curriculum choices a lot more difficult, uncertain and timely. It is as though one leaves also aside a well-known trusty beacon
How can this be replaced by such a vague concept as relevance for life-world situations ? What relevance for which situations in whose life-world ? Can a

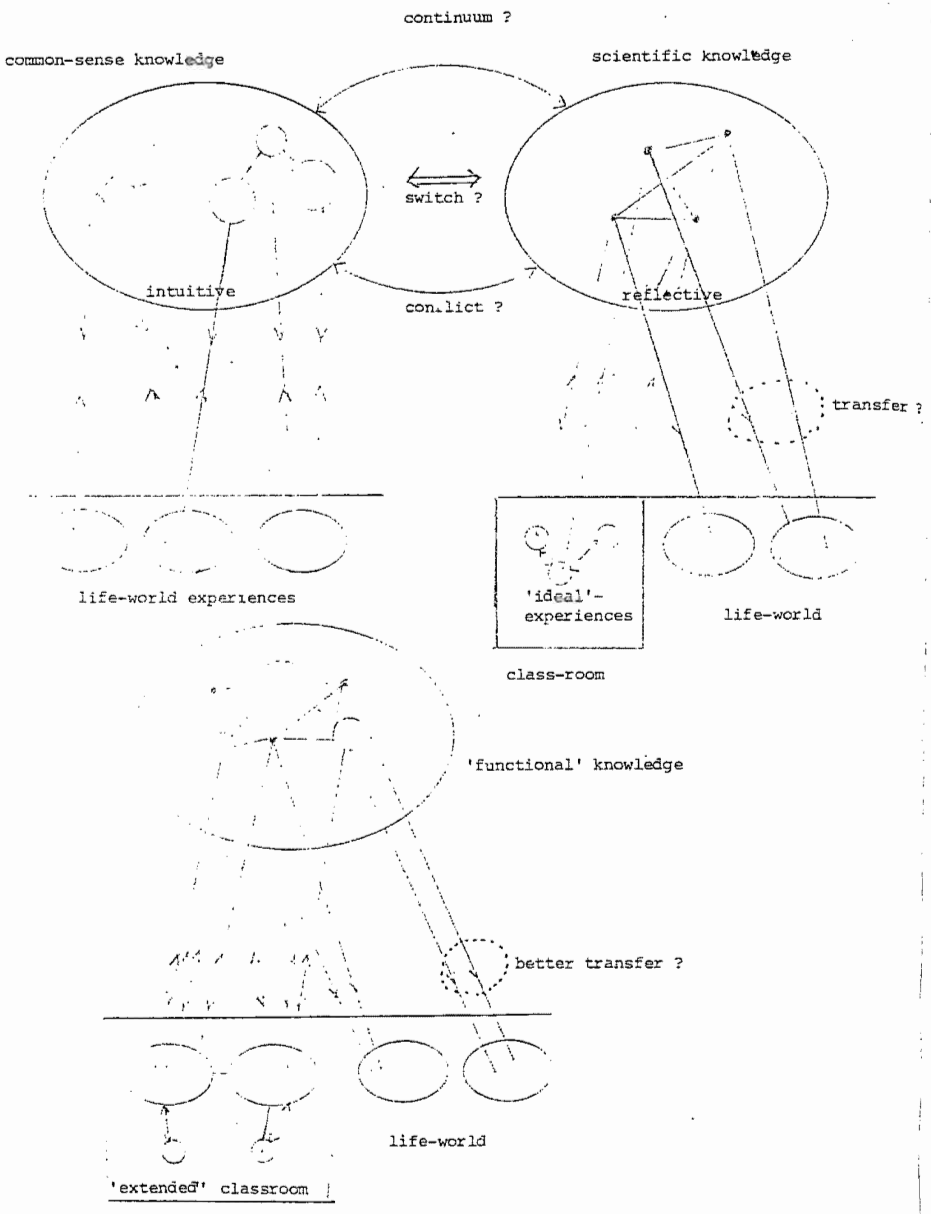
certain necessary consensus ever be reached about such phrases ? This certainly constitutes a serious problem. One could say that at least two 'schools' can be distinguished, which I would like to call the 'pedagogical' and the 'sociological' school.
The pedagogical school starts from the personal and subjective life-world of a pupil. It tries to relate the teaching to and start from knowledge and experiences pupils already have. Relevance means in this case, that pupils should experience it as relevant for their own life-world.
The sociological school describes the concept of the life world more objectively, to enable the teacher or curriculum developer to make his choice of what he thinks to be relevant life-world situations for pupils.
Usually, life-world situations are deried then from three different 'sources', i.e. future educational and occupational perspectives; pupils' private lifes during their spare time at home or elsewhere; and the perspective of a responsible citizen who has to participate in democratic decision making.
As will be clear from the following, with regard to the age of our pupils in this unit we have adopted the latter analysis for developing our teaching about energy.

What kind of knowledge ?

Having decided about how and why we have dealt with the concept of 'life-world', the next question immediately shows up. What kind of knowledge is really functional in which situations ?
Now the traditional view in physics education is that whatever situation we are talking about, only scientific knowledge enables real mastery of it. Being able to understand scientifically what is going on means being able to predict and explain and thus being able to act rationally to master the situation, be it inside or outside school. This may be true in principle to a large extent, but it also asks often for an unrealistic high level of insight and skill in the use of such knowledge. Not even physicists themselves are always able to do so, I think, nor would it be wise of them to try, as in many life-world situations other types of knowledge seem to function much easier and more effective.
For instance, when my car is out of order I first always try to find out 'scientifically' what may be wrong; using hypothetical-deductive reasoning, experimenting, my relevant knowledge of thermodynamics, mechanics and electricity, etc. Unfortunately, I have to admit that my method mostly fails; it simply doesn't work, just as my car at such moments. The garage-mechanic whom I finally have to consult, however, acts quite differently. He doesn't even listen to all my diagnostical results, he doesn't reason 'scientifically' at all, but follows a simple recipe of actions, uses situational knowledge, and finds the solution without failure.
A simple example of a functional and succesfull type of knowledge, of an algorithmical nature, and of inadequate use of 'general knowledge'.
Of course one could possibly integrate both types of knowledge in this case, but from an educational point of view, would it be wise to so so ? I don't think so, neither for the education of future garage-mechanics, nor for the education of future physicists. And how about our pupils ?

Pupils' knowledge

In recent literature a distinction has been made between common-sense knowledge and scientific knowledge. And a debate is going on about whether it concerns two extremes of a continuum or a dichotomy. How qualitatively



different really are both types of knowledge ? From educational standpoint a very relevant and important question.
Recent research shows that childrens' common-sense frameworks (childrens' physics) appear to be a severe hindrance to the learning of conflicting scientific frameworks (physicists' physics). Undoubtedly an important result that cannot be neglected any longer in the teaching of physics, as has been done too much in the past. Now, among the adherents to a structure-of-physics-curriculum little question exists about the opinion that wrong life-world common-sence knowledge has to be replaced by right scientific knowledge of physics. The only point that can be discussed seems to be about which teaching strategy and didactical approach suits this goal the best.
If both types of knowledge are only extremes on a continuum-scale, than a step-by-step approach may be appropriate. Start from childrens' knowledge, take their ideas seriously, but lead them gradually during their school-career into the world of physics ('Auf dem Wege zur Physik', as Wagenschein has put it).
However, according to others (see Redeker, 1982) such a procedure has to fail as it midjudges the fundamental difference between common-sense and scientific knowledge. Then, a more 'revolutionary' approach, of emphasizing explicit conflict and the peculiarities of physical knowledge, whenever it seems appropriate, may work better. If I interpret her correctly, Solomon (1983) argues recently still differently as, to her opinion, what has to be done is not so much the replacement in pupils' minds of a domain of common-sense knowledge by the corresponding scientific domain but pupils have to learn to switch between both domains according to the functional and communicational demands of the actual situations pupils encounter.
In principle I agree completely with this position and as it emphasizes functionality, it comes closest to the position we have taken in our curriculum. Nevertheless, in our 'functionality-concept', I think, we are treating the problem still differently.
Whether or not, and if so to what extent, common-sense knowledge has to be 'extinguished', or switching to scientific knowledge has to be learned, depends upon the life-world context actually chosen. If physical knowledge can really help pupils to master context-situations better than common-sense knowledge, it is important that they learn to do so. But in other situations within the same context, it may be quite functional and sufficient to build upon, extend and enrich common-sense knowledge by relevant scientific aspects. Of course one could say, that such teaching may sometimes be far away from teaching physics. But as I have explained before, such a choice is a result of our pedagogical position.

4. TEACHING ABOUT ENERGY AND ENTROPY

A main question we had to face concerning the construction of our unit is what knowledge of physics does really help a pupil to act more consciously with regard to the energy-issue, both in his personal and social life. However, does such knowledge exist at all ? Does physical knowledge ever influence the 'energy-behaviour' of people ?
For instance, would it be true that physicists behave more 'responsible' with regard to the use of energy ? Would they have 'better' opinions and attitudes in this respect ? Or is most of their knowledge not functional for their behaviour within the social energy-context ?

By the way, what do we mean above, when we speak about 'more responsible' and 'better' ?
To reach the goal, stated above, is it really necessary to teach rules and concepts of physics to a considerable 'structural depth', or can we confine ourselves to a much more superficial 'enriching' of already present common-sense knowledge about energy-concepts ?
All these questions are easier to ask than to answer, and clearly, no unanimous answers can be expected. At the last GIREP-conference in Hungary (1981) it was stated that 'physics teachers in particular have the key in their hands to solving the future energy-situation', indicating an important role for the teaching of physics. However, in a recent brochure meant to inform the general public about the energy-issue in our country, it was stated explicitly that NO KNOWLEDGE of the physical concept of ENERGY is NECESSARY. And in a 200-page report, prepared by the Steering committee for our public energy-debate, only one chapter of five pages pays attention to the 'physics of the problem', under the title: energy in quantities and units, and that's all.
So, where does this leave us if one wants to develop 'functional energy-education' as part of a physics-curriculum

After intensive, lasting and sometimes vehement deliberations we have come to a number of decisions, which I will summarize here briefly. They serve as a background for the more detailed description of the teaching-unit itself, which follows here after.

As many of our pupils (though not all) have been taught a unit on 'Energy at home' in a lower grade, it was decided that in this unit on 'Energy and Quality', we should essentially broaden the scope. Therefore the social energy-issue was chosen as the 'recognisable and relevant life-world context', as I have previously called it, in which and for which our teaching should function. Therefore, the following questions were taken as the main guiding principles for the construction of the unit; for the pupil: 'How can I act 'wiser' with energy ? For the developer: 'What knowledge of physics can help a pupil to do so ?'

'Being wise with energy', to our opinion, involves acting more consciously from two different perspectives, which have to be closely related and confronted. A pupil, as well as any body else, uses energy daily in his personal life, and he has to form an opinion about the socio-political energy-problem, at a local as well as a national and international level. Both aspects are based on personal and social values, which thus have to be taken into account. Or, to put it differently, the energy-issue is strongly related to both the 'quality of life' and the 'quality of society', as they are perceived by everybody individually. This explains partly the term 'quality' in the title of our unit.

The other part being explained by the concept of 'quality of energy', which we regard as an important new way of looking at energy-use. Other main concepts in our unit are 'alternative energy-sources' and 'efficiency', in relation respectively to energy-sources in general and energy-conversions.

We do not think that a sharp physical definition and knowledge of the energy-concept is functional. A loose definition like: 'energy is the ability to do a job' seems to be sufficient. It has the advantage that it stays relatively close to common-sense ideas about energy.

For the same reason we do not treat conservation of energy as a fundamental law of physics which determines both the structure of matter and universe. In our unit, we use conservation of energy in the form of an energy-balance, which enables us to calculate how much energy is lost as heat in practical energy-conversions. This is done as, in our opinion, energy-loss and energy-consumption are the more important concepts which have to be explained. So, the sharp conflict between the scientific energy-conservation-law and common-sense energy-consumption is avoided.

Also, no sharp definition of heat as 'energy-transfer due to a temperature difference', well to be distinguished from internal energy, is necessary. So, again a possible conflict with common-sense knowledge is avoided. We think it to be sufficient that heat is considered as a form of energy, which has something to do with chaotic thermal motion.
Due to this chaotic nature, it is a special degraded form of energy, which, unfortunately, has a very important role to play in the everyday energy-practice.

So let's be wise with energy;
save it, both in amount and quality '

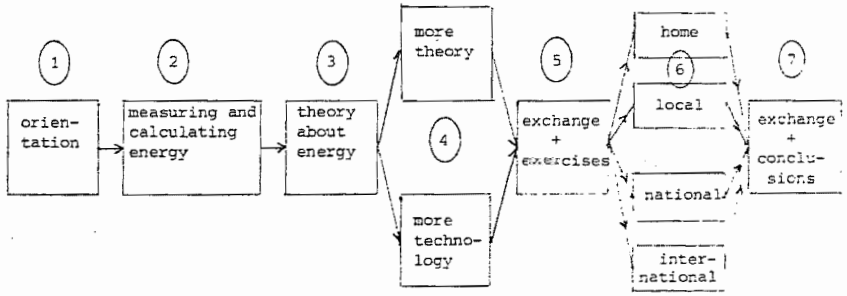
Sofar some headlines, now some more details.

5. ENERGY AND QUALITY; a description of our teaching unit

Now follows a description of our unit as we have planned to revise it. The actual development still has to happen (september-november 1983).

For the pupils, the central theme of the unit is:
'How to be wise with energy,
both personally and socially'

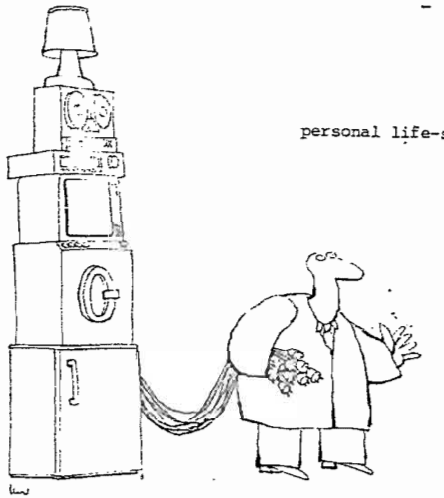
Unit-structure and lesson-planning.



number of lessons:

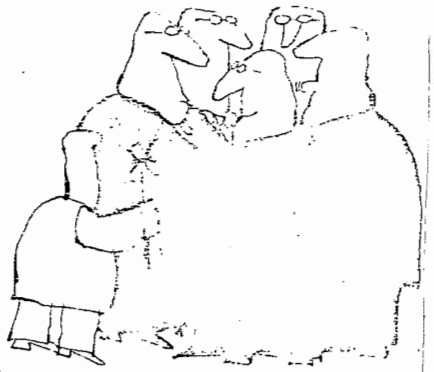
2	7	3	3	3	3	2

23



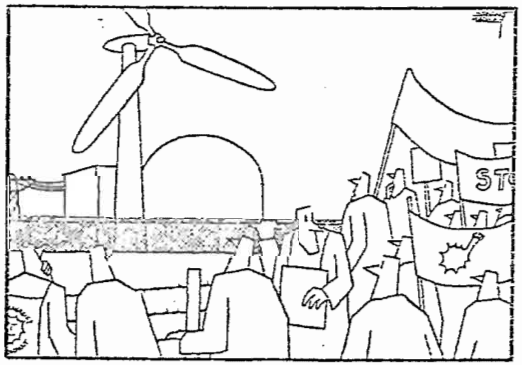
personal life-style.

and quality of life



personal values

and actions !



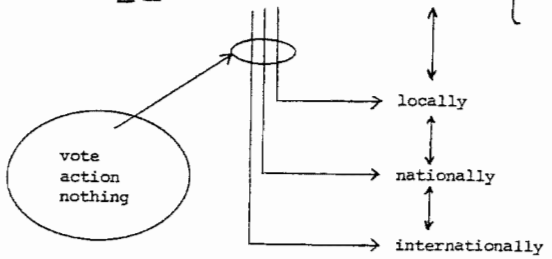
public energy-debate

who is going to decide ?

1. Orientation

Regarding the energy-issue, several levels of personal influence can be distinguished and confronted.
So, our unit starts with the question:

What can I do, as a citizen and as a person → personal life-style ↕ energy-use at home/work



To a certain extent pupils can be made aware of their personal life-style as follows. They can make an inventory of their daily 'energy-actions', if necessary with the help of a reference list. Secondly they can be asked whether those actions are taken consciously and 'wisely' with regard to the energy-issue. To what cost are they prepared to improve their energy-behaviour, and how would that be possible. For instance, if they had to cut their energy-use by, let's say, 50%, what would they be prepared to give up of their normal luxury ?
From such an activity, certain typical 'value-profiles' with regard to thinking about energy and life have to be extracted, in order to confront them with the value-profiles underlying a next activity.

This regards a comparison of two extreme 'energy-scenario's' that have been developed for our public-energy debate. These scenario's make clear that the future-policy of our government is of decisive importance for how our society is going to develop. Decisions have to be taken regarding such 'variables' as: economic growth, future energy consumption, (un-)employment, environmental protection, energy-research-policy, energy-policy, private consumptions, etc.
Clearly, the issue is very complicated. So, who is going to decide ? The energy-experts, extra-parliamentary action-groups, the government and parliament or the general public ?
Both activities should make clear that the energy-issue is related to what we call quality of society and quality of life, about which pupils have to decide for themselves.

After this general introduction, pupils have to choose individually on which 'level of influence' they wish to concentrate their activities further on, during this unit.
Ideally, all further activities, including the gathering of information from newspapers, magazines, etc. have to be related to a particular level of interest.

So that at the end of the unit, a well-prepared discussion and confrontation can take place, which confronts the perspectives from different levels. Is being 'wise at home' also 'wise for the Netherlands'?

2. Measuring and calculating energy

This chapter starts with the question: 'What is energy actually used for ?' The answer is given by considering two energy-flow-diagrams which look very much alike.
The first describing the energy-flow through 'an average household' and the second the energy-flow in our country as a whole. In both cases, a number of energy-sources are used, all kinds of conversions take place and in the end a great amount of energy appears to be lost.
So, questions as: 'has one been wise with energy', and 'how can this be improved' arise almost automatically. Therefore we have to take a closer look.

Pupils get a number of relatively short experimental and/or theoretical tasks, on which they have to work in small groups. The tasks concern a number of systems, both large and small, which 'use' or 'generate' energy, such as: dynamo, car, train, electric bulb, windmill, electric power-station, accumulator, central-heating system, etc. Each time they have to look at those systems form the following perspective:
what energy goes in; what comes out, what happens in between;
what energy is useful and what energy is lost;
how efficient is the system, and how efficient are the energy-conversions.

In these tasks pupils have to use knowledge and formula's learned in previous units within a different context, but also information from newspapers, etc.
They have to apply formula's like: $W = F.s$, $P = V.I$, $E = V.I.t.$, $E = c.m.T$, $E = m.g.h.$, etc. as rules to calculate amounts of energy.
And they have to measure efficiencies for relatively unknown systems as: solar-energy collectors, flywheels, photo-electric-cells and wind-turbines. If necessary heat-losses are taken into account to complete the energy-balance of the systems.

3. Heat-machines and quality of energy

As is clear from the flow-diagrams and the diversity of systems considered in the former chapter, heat plays a particular and particularly important role in the world of energy.
In all systems, energy gets lost as heat. What does that mean ? Moreover, nearly all 'consumed' energy is first 'produced' in heat-machines, from burning coal, oil, natural gas, or even uranium. And precisely those machines appear to have a low efficiency and thus large energy-losses. Can't this be improved ?
And if not, do we use this 'expensive' energy from heat-machines intelligent enough ?

Those questions ask for some theory.
In every real energy-system, some energy is 'lost as heat'. This means not that energy itself is lost, but that part of the input-energy is not available for the job to be done but is conversed into molecular energy of the system itself. And finally by cooling the system, the heat is lost into the environment.

quality of society

Can such a loss be prevented ? Well, of course one could try by better insulation and lubrication, etc.
Or by using the heat for heating of something useful instead of the environment, or for doing some other job ?
Unfortunately, there are some restriction to this game, which we make plausible by having a closer look at heat-machines. Such machines need always a temperature difference to work, which can only be made plausible for this moment. We then provide the pupils with the maximum-efficiency formula which is not derived. It simply expresses the fact that a necessary temperature difference entails a necessary efficiency effect.
Thus heat-machines can only convert heat partially into work, which is not an artifact of the machine but of heat itself.
Therefore heat of a high temperature is more valuable than heat of a low temperature.
Or, more generally, according to the efficiency with which an energy form can be converted into work, we speak of the quality of energy. And thus heat of a low temperature appears to be a strongly degraded form of energy. So, if we want to be wise with energy, we have to save not only its use but also its quality.

It will be clear that the theory described sofar is not of a very fundamental, explaining character. These theoretical notions have to make clear only that certain actions are not possible in practice and that some actions are more intelligent than others. Or, to put it in one phrase: this theory has to be functional '

4. First differential period
As usual, we have in our unit two differential periods. In the first pupils may choose between either more theory or more technology.

The optinal theory is now of a clearly different, more fundamental and explaining character.
First, the role of heat appears to be even more important as already told in the previous chapter. Finally all 'used' energy ends up as heat, that only heats the environment. Thus as useless heat of no quality. This raises the question: can this apparent one-way-traffic not be turned into a two-way-traffic ?
Therefore we have to look deeper into what actually takes place, i.e.: that ordered energy forms turn into disordered heat of finally low temperature. The reverse is highly improbable, which means that no work can be obtained spontaneously from a one-temparature environment. This explains that heat-machines have to work on a temperature difference, and thus with a restricted maximal efficiency.

However, pupils interested in technological practice may choose te learn more about practical ways of efficiency-improvement, heat-pumps, total-energy-systems, heat/power systems, etc. The latter being relevant ways of putting the quality-of-energy concept into practice.

5. Exchange and exercises
After a differential period an exchange period is planned. Pupils have to report then to each other about what they have done and learned. From these reports everybody is expected to learn the main lines, sothat these can be regarded to be common knowledge. It will be clear that such a demand asks for a certain quality of the reports as well as for a positive critical

attitude of the 'receivers'. Both can be considered as important learning effects. Apart from this exchange of experiences, some exercises have to be made to digest what has been done so far.

6. Second differential period
At the end of the unit a free differential period has been planned, which means that this period is not expected to lead necessarily to common knowledge.
Pupils have to study, design or criticise an energy-supply-system according to their own previously chosen level-of-interest.
Information from newspapers, magazines, etc. that has been gathered during the teaching of the unit can be used. Aspects related to quality of life, quality of society and quality of energy have to be taken into account wherever possible and functional.

7. Concluding exchange and confrontation
Finally in a closing discussion pupils have again to report about their findings and opinions. Our main goal for this discussion is that a confrontation of level-arguments can take place. Is what may be wise at a personal level also of any relevance nationally ? And the reverse ?
What does it mean to be wise with energy, both personally and socially ? Are we, each in his own way, really prepared to do so ?

FINALLY
This concludes a detailed description of what we intend to do. What I described here is a drastically revised version of a first try-out.
A first version which was clearly a half-way product due to the fact that we as developers were mainly developing ourselves. Although this process will never end, we hope that we have travelled for enough now, to be able to work out a more balanced version.
An extensive evaluation study has been planned to see which of our goals will be reached to a certain extent. In particular we are eager to learn more about what we mean by functionality. Would it really be true that the teaching of a unit like this is functional for outside school life-world situations ?
And if so, in what way and for how far. May be in the future I'll be able to report about this. So, goodbye and till then '

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So, let's be wise with energy
save it, both in amount and quality !

THE RELATIVE MERITS OF THE PHENOMENOLOGICAL AND STATISTICAL APPROACH TO THERMODYNAMICS

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Contrary to the common belief, classical thermodynamics developed along purely macroscopic lines is not easy conceptually. Its simplicity, being based only on the familiarity of macroscopic parameters used, is rather deceptive. The subtle reasoning involving heat engines seems often artificial to our students. Statistical physics, on the other hand, is held in somewhat fearful respect even by seasoned physicists due to its sophisticated mathematical apparatus. It is no wonder that, at least in high school physics teaching, the phenomenological approach prevails.

Since the advent of PSSC and Nuffield courses, however, both the people responsible for physics curricula and physics teachers have realized that this need not be so. The inroads are being made slowly both upon the traditional way and content of teaching. Let me discuss the issue using as an example the present status of thermodynamics teaching in Polish high schools. Our local experience can be looked at from the following points of view.

1. The teacher's point of view

Having spent a lot of time teaching kinetic theory of gases, the teachers goes with his 16-17 years old students through the two laws of thermodynamics on a purely macroscopic level. She or he faces then the choice between simply saying how, and attempting to show also why. The standard textbooks are of no help here, as they stop with presentation of the Second Law in terms of efficiency of the Carnot engine. The curriculum aimed at students with interest and ability

for physics and mathematics includes also the concept of entropy; the word itself sounds a bit embarrasing at school. Fortunately, this quite often decides the teachers to attempt the statistical approach, which allows to understand the meaning of entropy, and to give his or her students the inside story.

Introducing the concepts of microstate, macrostate and thermodynamical probability seems a good start. To this end the teacher can present the simple exampke or arranging e.g. 4 distinguishable particles or counters in two compartments. Counting the number of ways the counters can be distributed in two compartments can serve as a vehicle to introduce the method that will be used consequently. Counting the number of ways turns out to be the clue to predicting which way any process will go. Here one borrows from the Nuffield Advanced Physics Course [1] both the method and the moral that what happens is what happens in many ways. The statistical origin of irreversibility is thus easily seen. If a system is in a state of low probability and we remove some constraints, it will spontaneously evolve into a state of higher probability. At this stage one can tentatively suggest that a quantity related to probability of a stage could be useful, in the sense that its growth points in which direction things will develop. We may even call this quantity "entropy". At the same time it can be noticed that the energy conservation law gives us no hint in which direction a process will go. On the other hand, spontaneous forming of a local vacuum in, say, the upper south corner of a classroom is not forbidden, but the probability of its occurence in a meaningful time scale is negligible. Having the students work with the numbers is very instructive here. This is also a good moment to talk about fluctuations, which will surface sooner or later.

Connecting entropy to the direction of energy flows is more difficult. However, if the teacher feels his class is up to it, he can use the Einstein model of solid and the

quantum shuffling game [1]. The game even with 6x6 chessboard is time-consuming, but it is wise to give the students the feel of it before they look at the results obtained for large numbers of oscillators and quanta. We hope to produce the computer films eventually; right now a set of transparencies will do. One can tie temperature to the steepness of distributions of number of oscillators vs. number of possessed quanta, and look at what happens when a "hot crystal" and a "cold crystal" come in contact. Again counting the number of ways proves to be very fruitful, but the actual calculations can be followed only by most advanced students and require additional time.

On the whole, even if this approach, as done by us, seems to involve some necessary hand-waving, it helps to develop an intuition, and the rigorous calculations are of secondary importance here. The random simulation methods are particularly useful since they predict the average behaviour.

These ideas have been presented repeatedly for the last eight years at various seminars for teachers and have formed a sort of folklore; some more precise presentations have been published lately [2,3], which will hopefully encourage more teachers to venture into this relative novelty. I would not dare to estimate how many teachers adopted this version, or at least part of it, but those who were tempted and decided to follow it have found it very rewarding and have stuck to it. Of course it requires an additional effort and careful planning, which, without the general rebuilding of the curriculum, involves stressing various issues when they appear in order to prepare the students for what is coming. The close cooperation with maths teacher is also necessary.

One of the reasons that most teachers still follow exclusively the macroscopic approach is that they were brought up on it. Besides, school is a very conservative institution; this is both bad and good, since in all long-term projects caution is necessary. The young teachers, however, tend to

imitate their own teachers' style and even repeat the contents. They probably feel safer this way.

2. The student' point of view

The necessary (but not prohibitively difficult) mathematical apparatus that is supposed to scare the students away can be built up gradually, and in fact the 12 years olds have their first encounter with probability in their math lessons. Another thing is that simulation games, providing mathematical experiment and thus helping to avoid more complicated derivations, are entertaining and stimulating, and the students are apt to spend more time on them voluntarily than on typical kind of homework. (Since the GIREP'81 Conference, [4] where the author learnt how to do it, we have organized for teachers several workshops on simulation games. Having played themselves, the teachers encouraged their students to play, which proved a great success.) Finally, it is a great relief to learn that the disorder in one's room is due not only to one's sloppiness, but also to the fact that there are much more "untidy" than "tidy" ways of arranging things. Realizing this makes the statistical approach dear to a teenager's heart.

All of it, even if not very formal, helps to develop the early intuition, the lack of which can be a hindrannce. Here follows my last point.

3. The university teachers' point of view

It is not very democratic to focus one's attention on the "cream of the cream", i.e. on the bright young people who decide to base their careers on physics and enter the university, but one cannot help observing regularities. At some stage they have a one semester course in statistical physics. Having managed successfully such hurdles as very advanced classical mechanics, quantum mechanics and electro-

dynamics, they encounter here a barrier of surprising height. Both parties are surprised - the students and the teachers. It is my belief that the barrier is to some extent psychological and originates in high school where the students either never encountered any statistical approach or were told it was beyond their understanding. This is really a vicious circle, because the students who never had it at school (and therefore lack the intuition) tend to find statistical physics at the university difficult, so when they come back to school they avoid it in their teaching, both from dislike and lack of confidence. Thus they impose their own bias on their students and may be helping to perpetuate the pattern.

It is superfluous to list all the advantages of the elements of statistical approach. It is therefore a great pity that in chemistry courses in our schools the need for it never appears. It would be a firm support to these physics teachers who feel that this is a good way to teach. What is more important, it would show our students that we are dealing with one world.

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A STATISTICAL WAY TO SECOND LAW AT 17+ IN HUNGARY

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The teaching of the Second Law in Hungary offers a very good example for the evolution of a pedagogical concept during the experimental teaching, by the fights against the conservative side and with the help of the comparisons obtained at international conferences. By the last remark I mean we have stolen many ideas from other countries. Those who visited Hungary frequently may to be sure they have become our victims in this respect. (They may become honorary members of the Hungarian Physical Society sooner or later - as a recompensation.)

Why do we teach the Second Law?

"Energy is conserved. Then why does one complain about energy crisis?!" - pupils may ask - "If there is a scarcity of energy then why do we disperse it in the cooling towers of the power stations?" These questions offer motivations which connect the subject to everyday life, to newspapers.

But there is another motivation, and I believe this is more exciting for "philosophycal" minded age group of 17+. According to everyday experience, any change in an aggregate of many elements is irreversible. How comes that Nature knows: what's earlier, what's later? How shall we be able to predict the future? (In earlier years pupils have studied mechanics, so they know: the Newtonian Laws are symmetric with respect to time reversal.)

If we want to answer these questions we need to teach Second Law on a more general way than the limitation of the efficiency of heat engines. Intending to make use of the formula $\Delta S \geqslant Q/T$, a picturesque introduction of entropy S is

needed. This can be done - as we believe - just on a statistical way.

Earlier years

Physics and chemistry are not well coordinated subjects in Hungary. - Chemistry starts at the age of 12+ (for the whole population) with introducing the electron structure of atoms (!?). They use the concept: "the world consists many atoms and molecules" without any experimental foundation. Just for this reason physics (starting at age 11+) offers a few pupils' observations to show that "there are many tiny particles around us in random motion."

Later, at the age 14+ about 20% of the children enter grammar school. Here in the first year of physics pupils discover the existence of molecules and atoms by their own experiences. (In the first year there are 60 physics lessons and the pupils make measurements and observations almost at each lessons but 25 whole lessons are for pupils' activities.) My experience is that this is the first occasion in my pupils' life when they learn something not because it was invented by old and wise scientists, but because Nature told the children directly when they performed their own experiments in the classroom - or in the kitchen. I believe on this way our pupils get a deep and useful experimental foundation to conclude that the world is made of many-many atoms in random motion. In this first years there are four main areas: 1) Orientation about I. and II. law by very qualitative observations; 2) Gases: measuring the temperature with gas thermometer on the basis of kinetic gas model, $pV = NkT$; 3) Liquids: measuring and modeling of surface tension, boiling; 4) Solids: measuring and modeling crystal lattice, heat capacity, melting, thermal dilatation.

Statistical mechanics at 17+

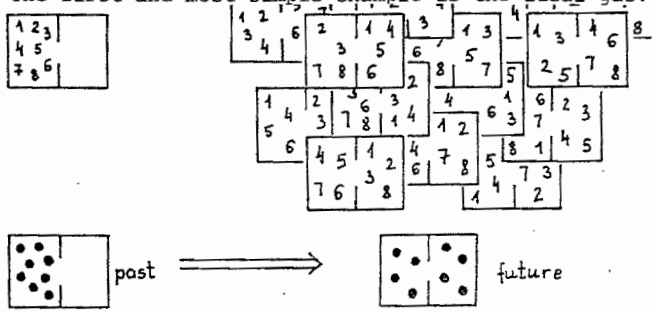
The Universe consists very many atoms. For Nature, each molecule is of equal importance. A given arrangement of molecules has the same probability as any other one. Descriptions of an aggregate, are called microstates iff they are equally probable.

But: man has to survive so he does not bothers to make difference among several molecular arrangements. If there is gas in a room, we are not interested which oxygen molecule enters our lungs, for us it is enough if there is oxygen in the room. If the door is open, we can interested in the density distribution of air in the two rooms, but it is of no importance which molecules are in which place. We are interested only in the macrostate!

All microstates are equally probable so the probability for the occurance of a macrostate is proportional to the number Y of the microstates representing this specific macrostate. This knowledge is enough to predict the arrow of time for the natural processes! In a closed system $Y(\text{past}) < Y(\text{future})$ for any change.

The most interested pupils have asked: how can I define microstates so that they will be equally probable? The teachers know: those states specified by quantum numbers are equally probable. But the pupils have not learned yet about quantum mechanics. So we can say to them: "Try to give a definition of the microstates based on common sense! If the conclusions fit to experiences, the definition of microstates has been good."

The first and most simple example is the ideal gas.



The second example is solid. N localized atoms share r energy quanta. For Nature each atom is of the same importance, therefore any distribution of the r energy quanta has the same probability. The microstates of a solid can define by giving the number of energy quanta for each atom.

Richard Feynman likes the following story:

"I do not know if you have ever had the experience - I have - of sitting on the beach with several towels, and suddenly a tremendous downpour comes. You pick up the towels as quickly as you can, and run into the bathhouse. Then you start to dry yourself, and you find that this towel is a little wet, but it is drier than you are. You keep drying with this one until you find it is too wet - it is wetting you as much as drying you - and you try another one; and pretty soon you discover a horrible thing - that all the towels are damp and so you are. There is no way to get any drier, even though you have many towels, because there is no difference in some sense between the wetness of the towels and the wetness of yourself. I could invent a kind of quantity which I could call 'ease of removing water'. The towel has the same ease of removing water from it as you have, so when you touch yourself with the towel, as much water comes off the towel on to you as comes from you to the towel. It does not mean there is the same amount of water in the towels as there is on you - a big towel will have the same dampness. When things get to the same dampness then there is nothing you can do any longer."

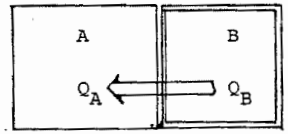
(R. Feynman, The Character of the Physical Law, MIT Press; a lecture held at Cornell University in 1964.)

Wetter: increased ability to give off water	Warmer: increased ability to give off energy
...does it contain more water?	...does it contain more E?
...acryl or wool towel?	...material quality?
...small or large towel?	...small or big body?

Wetter: gives water to the drier one spontaneously.

Warmer: gives energy to the colder one spontaneously.

Let us tell this on the language of microstate



"spontaneously" means:

$$Y_{A+B}(\text{future}) > Y_{A+B}(\text{past})$$

since

$$Y_{A+B} = Y_A \cdot Y_B$$

thus

$$Y_A(\text{future})\, Y_B(\text{future}) > Y_A(\text{past})\, Y_B(\text{past}).$$

Stop for a minute! Physics likes such state variables which are extensive (i.e. sum up, as mass or energy) or intensive (i.e. level up as pressure or concentration). The number Y of the microstates is not of these types, it "multiplies up". By taking the logarithm of the number of microstates, however, an extensive quantity can be obtained.

$$\log_a Y_A(\text{future}) \cdot Y_B(\text{future}) > \log_a Y_A(\text{past})\, Y_B(\text{past}),$$

$$\log_a Y_A(\text{future}) - \log_a Y_A(\text{past}) > -\log_a Y_B(\text{future}) - \log_a Y_B(\text{past})$$

$$\Delta \log_a Y_A > -\Delta \log_a Y_B.$$

On the other hand this change of the number of microstates was caused by the heat. Heat went into body A from the body B:

$$Q_A = -Q_B.$$

Let us devide this equation by the earlier inequation

$$\frac{Q_A}{\Delta \log_a Y_A} < \frac{Q_B}{\Delta \log_a Y_B}.$$

If the body B is characterized by larger value of the expression $Q/\Delta \log_a Y$ than it has a higher ability to give off energy, i.e. we call it warmer, i.e. we say it to have a higher temperature T. On this way we can assign a value to temperature: it is proportional to $Q/\Delta \log_a Y$.

$$\frac{Q}{k\Delta \log_a Y} = kT$$

Let us imagine two bodies, both of them get same energy Q = 1J. In the warmer one the change the value $k\Delta \log_a Y$ is smaller then in a colder one. The same energy can make larger disorder in a colder body than in a warmer one.

Let us apply this definition of temperature to an ideal gas when it expands from V to V + ΔV at constant temperature T, which means work performed by the gas. The energy of the ideal gas does not change so heat

$$Q = p\Delta V. \qquad (1)$$

has to go into the gas. On the other hand when the volume increases from V to V +ΔV the number of the microstates increases:

$$\frac{Y(V + \Delta V)}{Y(V)} = \left(\frac{V + \Delta V}{V}\right)^N = \left(1 + \frac{\Delta V}{V}\right)^N$$

thus

$$k\Delta \log_a Y = k \log_a Y(V + \Delta V) - \log_a Y(V) = k \log_a \frac{Y(V + \Delta V)}{Y(V)} =$$

$$= kN \log_a \left(1 + \frac{\Delta V}{V}\right).$$

Let us put the expressions (1) and (2) into the definition of temperature:

$$T = \frac{p\Delta V}{kN \log_a\left(1 + \frac{\Delta V}{V}\right)},$$

$$NkT = pV\frac{\frac{\Delta V}{V}}{\log_a\left(1 + \frac{\Delta V}{V}\right)}.$$

This is almost the equation pV = NkT, which is well known from earlier studies! Intending to measure the temperature with gas thermometer in kelvin it is necessary to choose a special basis e for the logarithm on such a way that

$$\frac{\frac{\Delta V}{V}}{\log_e\left(1 + \frac{\Delta V}{V}\right)} = 1.$$

Pupils can find out with a calculator very soon that $e \approx 2{,}72$. (In Hungary log. nat. is not tought in the secondary school mathematics.)

Let us try to apply our definition of temperature in another area! (Only for talented pupils.)

In a solid N atoms share the total energy E inform of equal energy quanta ε_1. (Albert Einstein proposed this model for solids in 1907.) How many microstates does this solid have?

If r = 0, then Y = 1. If r = 1, then Y = N. When the solid gets one quantum more, the number of its microstates will increase.

And now a tale comes. Let us think on a village street where geese are led to the field. N gooseherds and r geese can go on Y different ways. (The first is always a gooseherd.)

A new goose arrives from a yard. This new goose can follow a gooseherd (N) or a goose (r). The number of the new goose lines is (N + r)Y. But for us a goose is just a goose, from afar any of the r + 1 geese might be the NEW one. So the number of the different goose lines will be (N + r)Y/(r + 1).

The pupils understand: the gooseherds are models for atoms, the geese are for energy quanta of that atom (gooseherd) which walks in front of them. And a specific goose line represents a specific microstate (a specific distribution of energy quanta among the atoms of the solis). The number of the microstates will increase by a factor (N + r)/(r + 1) or if $r \gg 1$, it will increase by the factor (1 + N/r) when the solid get a new energy quantum. When the solid gets the energy $Q = q\varepsilon_1$ ($q \ll r$) than the number of its microstates will increase:

$$\frac{Y(r + q)}{Y(r)} = \left(1 + \frac{N}{r}\right)^q.$$

When the solid gets this amount of energy at temperature T, then

$$T = \frac{Q}{k\Delta \ln Y} = \frac{q\varepsilon_1}{k \ln\frac{Y(r + q)}{Y(r)}} = \frac{q\varepsilon_1}{k \ln\left(1 + \frac{N}{r}\right)^q} = \frac{\varepsilon_1}{k \ln\left(\frac{N}{r} + 1\right)}.$$

$\frac{N}{r} = \frac{N\varepsilon_1}{r\varepsilon_1} = \frac{\varepsilon_1}{\bar{\varepsilon}}$, thus $\ln\left(\frac{N}{r} + 1\right) = \ln\left(\frac{\varepsilon_1}{\bar{\varepsilon}} + 1\right) = \frac{\varepsilon_1}{kT}$,

$$= \frac{\varepsilon_1}{e^{\frac{\varepsilon_1}{kT}} - 1}.$$

If $kT \gg \varepsilon_1$, ie $\varepsilon_1/kT \ll 1$, then $e^{\frac{\varepsilon_1}{kT}} \approx \varepsilon_1/kT + 1$, so

$$\bar{\varepsilon} = kT.$$

This result can be checked by measuring of heat capacity of solids. But $\bar{\varepsilon} = kT$ does not work for every solids. The diamond does not obey Dulong-Petit's Law, it has smaller heat capacity at $T = 25^{\circ}C = 298$ K than that following $\bar{\varepsilon} = kT$. At this point we may start introducing quantum mechanics.

The number Y of microstates is a multiplicative state variable. Taking its logarithm the quantity $S = k \ln Y$ will be an additive, extensive variable. We shall call it entropy.

On a picturesque way: S can be considered to be a measure of disorder. (For example a solid with no energy quanta, (r = 0) is in the unique state, and so its entropy is S = k ln 1 = 0: there is no disorder!)

In a closed system Y(future) $\geq$ Y(part), "$>$" is valid when there are processes going on and " = " is valid when there is a steady equilibrium. From this it follows that S(future) $>$ S(past), i.e.

$$\Delta S_{closed} > 0.$$

$\Delta S_{closed} = \sigma > 0$, when there is any change.

What can be said about entropy in an open system? $T = Q/k\Delta \ln Y$ consequently $T = Q/\Delta S$. If heat Q is introduced into an open system,

$$\Delta S = \frac{Q}{T} + \sigma.$$

During a natural process the disorder of an aggregate changes due to the heat coming from the environment and due to the events happening inside it. This is the Second Law.

This is just the main line of the teaching of statistical mechanics in Hungarian grammar school. There are about 20 lessons available for it.

Several applications are given as problems, like

1. The mankind had learnt physics on the sky (i.e. in astronomy) and not in the lab. Why?
2. Ice melts at a pressure $10^5 N/m^2$. How many times more microstates are in 1 kg water at 0^oC, than in 1 kg ice of the same temperature?
3. The air pressure on the Mount Ararat (of the height 5156m) is half of the air pressure at see level.
   What will be the boiling temperature of water on the top of the mount?
4. In the pressure cooker the ventil produces $1.6 \times 10^5 N/m^2$ pressure. What is the boiling temperature of water in it?

   In the pressure cooker the beef will be cooked four times faster. How large can be dissotiation energy of the molecular bonds which break while cooking beef?
5. It is hot at home in the summer vacation. Can Johnny make cooler in the apartment if turns on the refrigerator and he opens its door?
6. Calculate the efficiency of heat engine working with a heat of T_1 = 373 K and a cooler of T_o = 280 K! (See the Appendix!)
7. There is a mountain observatory, which needs 100 kW for heating. There is only 50 kW electric power available. What to do?

The problem's solving helps to get a deeper understanding. But the same results can achieved if pupils are using fundamental laws in different area of physics. In the last year of grammar school when the Second Law is tought, elementary quantum mechanics leads to semiconductors and nuclear physics leads to fission and fusion reactors. In the last weeks of the grammar school the physics lessons deal about the evolution of Universe: from the Big Bang to the present scientific-technical problems of mankind (electronics, energy, crisis, social responsibility,...) The Second Law is very useful in these topics!

Paul Valéry wrote: "Two perils threaten the world: order and disorder." Indeed, complete order means zero kelvin without any random motion, without any chance to change, without life. Complete disorder means complete chaos without any structure, without any direction of time, without life. At the end of their physics studies our pupils may understand: the world is beautiful because it is somewhere between these extrems. Events follow each other toward the direction of the larger disorder. The Second Law offers possibilities, man may choose from among them, man can design microcomputers and power stations, learn physics and make love.

An answer to Paul Valéry was given by my favorite Hungarian poet József Attila (his name is that of my school):

Come liberty!
Bearing order for me.
Teach me with mild words,
But also let play your serious shinning son!

APPENDIX

The Industrial Revolution became interested in substituting man power by engines. The last century dream of inventors were an engine producting work out of nothing. The impossibility of such a perpetuum mobile of the first kind was shown by the understanding the First Law:

$$\Delta E = W_{in} + Q_{in}.$$

For a perpetuum mobile $W_{out} > 0$, consequently $\Delta E = -W_{out} < 0$, the energy of the engine decreases, finally the engine must stop working. But an engine transforming heat (obtained from the environment) to work (given to the environment) without loosing energy would not contradict the First Law:

$$\Delta E = Q_{in} - W_{out} = 0$$

if $W_{out} = Q_{in} > 0$. The problem arises from the Second Law

$$S = Q_{in}/T + \sigma . \quad (\sigma > 0.)$$

If heat is introduced, disorder increases in the engine, so it will soon stop working: a perpetuum mobile of the second kind is also impossible. The only chance to make work out of heat is that the engine gets vid of disorder. According to the Second Law $\Delta S = Q/T + \sigma$ the only way of decreasing entropy is by giving off heat. Heat will go spontaneously to a cooler place. So heat engine may work between a furnace (of high temperature T) and a cooler (of low temperature T_o),

as observed by Sadi Carnot in 1825. If the engine returns to its initial state after a cycle, its' energy does not change, $\Delta E = 0$, so

$$W_{out} = Q_{in} - Q_{out}. \qquad (*)$$

According to the Second Law, the change of entropy in the furnace $(-Q_{in}/T)$ plus in the engine (ΔS) plus in the cooler $(+Q_{out}/T_o)$ must be positive:

$$-\frac{Q_{in}}{T} + \Delta S + \frac{Q_{out}}{T_o} > 0.$$

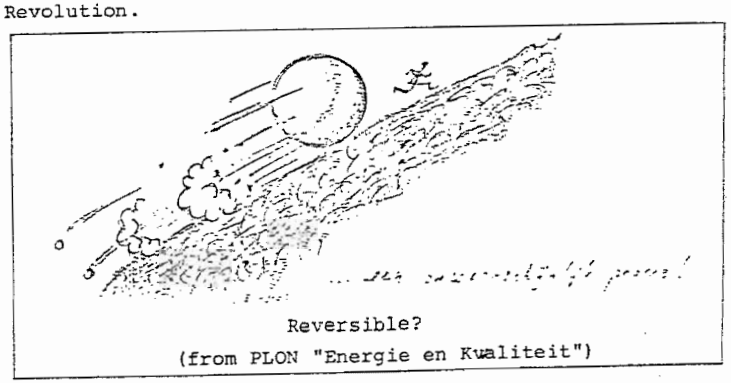
If the entropy of the engine returns to its original value after one cycle,

$$0 = \Delta S > \frac{Q_{in}}{T} - \frac{Q_{out}}{T_o} . \qquad (**)$$

From the equations (*) and (**) the efficiency of a heat engine can be calculated:

$$\eta = \frac{W_{out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} < 1 - \frac{T_o}{T} < 1.$$

This equation became a fundamental formula for the Industrial Revolution.



Reversible?
(from PLON "Energie en Kwaliteit")

TEACHING OF THERMODYNAMICS IN INDIAN SCHOOLS

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Like so much else in the Indian school curriculum, the teaching of Thermodynamics makes no concessions to the understanding of the subject or to any pleasure in its learning.

Thermodynamics is usually taught in the eleventh year of the twelve year school system and it constitutes one of twenty units which are spread over two years. The development is fairly conventional and, I am afraid, inadequate in terms of the time spent on it given the conceptual difficulties of the subject. It uses as a prerequisite a unit on the kinetic theory of gases in which Brownian motion, diffusion and evaporation of liquids are offered as evidence justifying a molecular description. Following a simple derivation of the equation of state of an ideal gas, it goes on to discuss the various gas laws, Avogadro's hypothesis, Graham's law of diffusion, the specific heats of gases and the law of the equipartition of energy.

The actual unit on Thermodynamics starts with the definition of temperature. How heat flows from a hotter to a colder body till such time as their temperatures become equal. It talks of the mechanical equivalent of heat, how heat is a form of energy which can be made to do useful work. It introduces the concept of internal energy in order to preserve the principle of the conservation of energy and thus proceeds to the first law.

It then goes on to the Kelvin - Planck statement of the second law : how not all the heat extracted from a reservoir can be converted to useful work. It introduces the Carnot cycle and talks of how engines in general are irreversible and have efficiencies lower than a Carnot engine.

The unit then deals with radiation from a black body, Kirchoff's law, the Stefan - Boltzmann law and concludes with a description of the black body spectrum and Wien's displacement law.

Instead of discussing the details of the course, which is undoubtably ambitious, I would like to take this opportunity to share with you what I consider to be some disturbing aspects of the recent developments in Indian school curricula - which I fear may not be untypical of the situation in other developing countries. In India there is a national council for educational planning. In their drive to modernise courses, our planners have lost sight of the fact that there is only so much that can be put into school syllabii if the students are to assimilate and internalise concepts. If new topics are to be brought in then some of the dead-wood must also be removed. Because this has not been done, our students have over the years become so burdened with new and "modern" topics that any understanding of the basic concepts has tended to fall by the wayside. We have now reached the tragic situation that although our syllabii have become more and more advanced, our students end up understanding less and less. They are not given enough time to internalise concepts, to weigh them up or to look at them from different viewpoints. Superficial acquaintance has slowly replaced conceptual understanding.

Another disturbing feature of syllabii revision has been the all but token service that has been paid to the training of teachers in the new topics. Not only are school teachers seldom consulted during the process of such revisions, but when any revision is decided upon, hardly any effort goes into training them in the teaching of these new and "modern" topics or in providing any back-up service which they can consult in case they run into difficulties. Consequently, teachers teach less and less of what they really understand and the portion of the course in which they find themselves out of their depth becomes increasingly larger. The students soon become aware of this situation and as a result there is little pleasure in teaching and even less joy in learning.

A third feature of this situation is that for most of the new topics that are introduced in an effort to modernise syllabii, there is little consequent addition of the necessary supporting experiments - both on grounds of cost and of the availability of the appropriate equipment in the schools. Improvisation can only go so far - and even that requires inputs of a kind which are not readily available in the schools. More and more, the teaching of Physics becomes a theoretical exercise and at its worst, reduces to the rote memorisation of a long list of esoteric facts that seem to defy all understanding.

It is only fair to say that the problems I have enumerated stem in large measure from the difficulties, both economic and administrative, of educating the very large numbers of students involved. But somehow our response has optimised the least important of the many pedagogic variables involved and unless we can take corrective measures soon our school system will be yet another addition to the class of systems which are subject to the inexorable grip of the law of increasing entropy.

- You look so excellent today.
- I was in the beauty parlor. It took quite a money to get rid of my entropy surplus.

CONFUSING POINTS IN THERMAL PHYSICS TEXTS

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Prolog

It is generally realized that thermal physics is a very hard branch of physical science. Thus, in Finnish we have a word play:

termofysiikka - hermofysiikka

Of course, this joke looses much of its rhythm in translation to English:

thermal physics - nervous physics.

Introduction

As was mentioned above, thermal physics is a difficult discipline. Thus, it is easy to understand that there exist several different approaches in the texts. The main purpose is to provide a better possibility to understand this obscure branch of physics. The rich variety of methods carries the possibility of erroneous or at least misleading ideas. In the following we will consider a few more or less typical cases of such situations.

Due to the existence of hundreds of texts in thermal physics, it has not been possible for this author to make a thorough study of this subject. Therefore, the examples presented here form only a casual collection. Some of the mistakes are clearly made inadvertently but are, however, harmful as they seem to pass from text to text. In addition some examples of mistakes of a more profound nature will be presented.

1 Entropy of Mixing

The molar entropy of a binary ideal mixture is

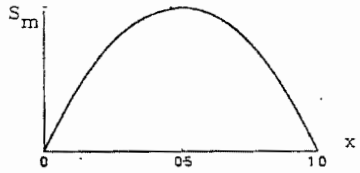
$$S_m = -R\{x \ln x + (1-x) \ln (1-x)\}$$

where x and 1-x are the mole fractions of the components.

The graph of entropy versus mole fraction resembles a second degree parabola. However, there is a fundamental difference, which appears at the end points of the graphs. In case of the parabola the absolute value of the derivative is finite at these points, whereas in the case of the mixing entropy it is infinite as is easily shown:

$$\frac{dS}{dx} = -R \ln \frac{x}{1-x} \longrightarrow \infty \qquad \text{when } x \longrightarrow 0$$

This latter fact dominates the pollution of the environment as the mole fraction of the pollutant (x) is generally very small ($x \ll 1$) as compared to the value for the pure substance ($1 - x \approx 1$). As the entropy always tends to increase, it means in this connection that the environment becomes polluted very easily, but the process of purifying is very expensive and difficult and in practice nearly hopeless. Therefore, it is very harmful that the graph of mixing entropy is frequently drawn inadvertently like a parabola. An example of this oversight can be seen in the textbook of Sokrates /1, p.131/, according to which the accompanying graph has been drawn.



2 An Equation of State for Solids

In the textbook of Desloge /2, p. 254/ we find a problem beginning as follows:

> "A certain solid obeys the equation $V = V_o - Ap + BT$ and its internal energy is given by $E = CT - BpT$, where A, B, C, and V_o are constants."

The meaning of the other symbols is self-explanatory. The equations are the so-called "thermal" and "energetic" equation of state, correspondingly. We should realize that these two equations are not independent of each other. If we accept the first, the second is determined mainly by the energy equation:

$$(\partial E/\partial V)_T = T(\partial p/\partial T)_v - p$$

Thus,

$$dE = (\partial E/\partial T)_v dT + (\partial E/\partial V)_T dV$$

$$= C\,dT + (V - V_o)dV / A$$

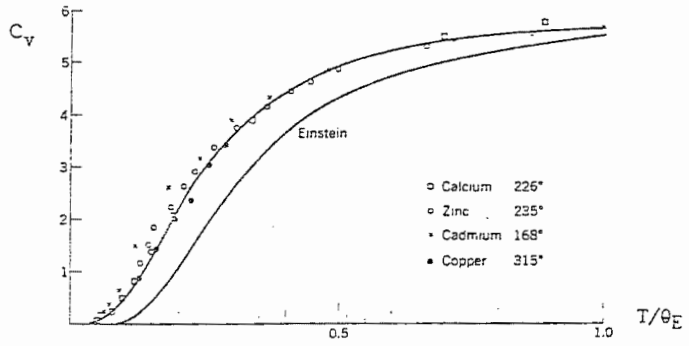
and, approximately

$$E = CT + (V - V_o)^2 / 2A$$

Thus, Desloge's equation for internal energy ($E = CT - BpT$) is incorrect.

3 Heat Capacity of Solids

It is common practice in textbooks to represent both the Einstein theory and the Debye theory. Both theories introduce the so-called characteristic temperature: the Debye temperature (θ_D) or the Einstein temperature (θ_E), correspondingly. The value of the latter temperature is about two-thirds of the former. However, in many texts the curves for molar heat capacity as a function of temperature are drawn using the value of the Debye temperature as the characteristic temperature in the Einstein case, too. This results in the Einstein curve deviating from the experimental values and the Debye curve noticeably throughout. The following figure is taken from Holman /3, p. 336/:



If the Einstein curve had been drawn with the proper characteristic temperature both curves should fit very well together. Only at low temperatures is there a marked deviation: approaching absolute zero the experimentally observed decrease in heat capacity goes as T^3 according to Debye theory and not exponentially as predicted by the Einstein theory.

4 Equation of State for Real Gases

It is well known that the treatment of real gases in terms of clusters is very complicated. Therefore, many authors try to use simplified methods. However, these methods contain generally very bad shortcomings as Rapp /4, pp. 185-190/ has shown. In this connection we will consider one specific point, only.

In many texts the simplified theory leads to the formula

$$(p + a/V^2)V = RT(1 + b/V)$$

where the notation should be self-explanatory. This formula does not include any phase transition. For that purpose it is too crude. Now, using the crude approximation

$$1 + x \approx (1 - x)^{-1} \qquad (x = b/V \ll 1)$$

in the previously mentioned formula one obtains the historically famous van der Waals equation of state.

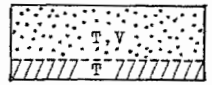
It is a generally known fact that the van der Waals equation leads to a phase transition. Therefore, it seems that the above-mentioned formula contains the property of phase transition, too, and seems to be the simplest statistical theory to do so. As we already know, the above-mentioned formula can not lead to a phase transition. The discrepancy results from the fact that two crude approximations have been combined to obtain a considerably better one: the van der Waals equation of state.

5 The Photon Gas

The textbook of Morse /5, p. 335/ treats the case of the photon gas in equilibrium at temperature T in a volume V. According to the text the number of photons N in volume V is not arbitrarily specified: it adjusts itself so that the radiation is in equilibrium with the constant-temperature walls of the container. After some reasoning Morse concludes that for a photon gas at equilibrium the chemical potential of the photons must be zero.

If Morse's reasoning were correct, it should apply, for example, to the following case; Consider a system of saturated water vapor in contact with a water reservoir.

The water vapor is held at temperature T and volume V. The number of water molecules in the vapor is not "arbitrarily specified".



water
vapor
water

This arrangement is wholly analogous to the case of the photon gas. Therefore, in this case too, the chemical potential of the vapor should be zero. On the other hand, we know that this is not true. Therefore, the reasoning in Morse's textbook is incorrect. Of course, it is true that the chemical potential of the photon gas is zero, but this fact is a special property of the photon gas.

6 Stirling Approximation

First we note that a critical reader should be displeased to see the Stirling approximation in the form

$$n! \approx (n/e)^n \qquad (n \gg 1)$$

as the approximation is only valid logarithmically:

$$\ln n! \approx n \ln n - n \qquad (n \gg 1)$$

There are a lot of confusing ideas in applying factorials to identical and, thus, indistinguishable particles.

In applications there can be cases where n is of the order of number one. Then the Stirling approximation looses its validity. Some authors believe that use of the better approximation

$$\ln n! \approx n \ln n - n + \frac{1}{2}\ln(2\pi n)$$

is a proper solution to the problem. However, this is not the case. In reality, the form $n \ln n - n$ is in principle more correct than any other form of the Stirling approximation.

7 Maxwell - Boltzmann Statistics

In cases where Maxwell - Boltzmann statistics is applicable we can write the entropy of a system in the form

$$S = k \ln W \qquad \text{where } W = \prod_i g_i^{n_i}/n_i!$$

The notation here should be self-explanatory.

Today this type of presentation should be considered to be wholly obsolete. Therefore, in this connection, we will consider one detail, only.

In applications we can have cases where the value of every g_i is one. This happens, for example, in the case of the harmonic oscillator. Thus, temporarily we have formally $W << 1$ and $S < 0$. These values are clearly unrealistic. This mistake is seen, for example, in Alonso and Finn /6, p. 482/.

8 The Meaning of a Partial Derivative

Consider a function of two independent variables. Differentiation of the function with respect to one variable means that the other variable is held constant. Mathematically this procedure seems to be very clear. However, application to thermal physics easily leads to confusion. To be more visual we take as an example the heat capacity of solids.

The heat capacity at constant pressure (C_p) is easier to measure than the heat capacity at constant volume (C_v). However, the latter quantity is more important theoretically. Both quantities are interconnected by the equation

$$C_v = C_p - T(\partial p/\partial T)_v(\partial V/\partial T)_p$$

This equation can be used to obtain C_v from C_p. Now we seem to be ready to compare the experimental and theoretical values of C_v. However, the case is not that simple. In the experimental C_v the volume is constant only t e m p o r a r i l y, whereas in the theoretical C_v the volume has the same constant value from the absolute zero on. Therefore, we must apply another reduction to the measured value of C_v. This turns out to be of the same order of magnitude as the above-mentioned reduction. There are two possibilities in performing this reduction. These differ from each other only slightly. One is introduced by Overton /7/ in 1962 and the other by this author at the same time (unpublished).

9 An Isolated System

In this last section we will discuss a case which is subject to some interpretation. In many cases authors seem to accept instinctively the definition of an isolated system as presented by Kreuzer /8, p. 324/:

> "There is a slight difference between thermodynamical and mechanical isolation of a system. In the first case, we demand that the average energy remains constant with thermodynamic fluctuations around this value still possible, whereas in the second case we must insist that energy is strictly conserved."

We could call this definition of a thermodynamically isolated system a "soft" definition.

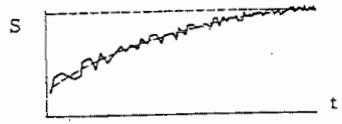
This author is not delighted with the "soft" definition, but prefers a "hard" definition according to which the energy of the thermodynamically isolated system should be considered to be strictly conserved and the fluctuations are, thus, not allowed.

The "soft" definition leads easily to confusion and vague interpretations. Of course, in practice we must always admit to some amount of fluctuations.

Entropy has the peculiar property that it will fluctuate always when one or more of the other quantities fluctuates. Let us suppose for simplicity that volume and number of particles are strictly constants. Yet, if we allow the energy to fluctuate we must allow entropy to fluctuate, too. Thus, if we accept the "soft" definition we must allow entropy to fluctuate in the state of equilibrium, whereas with the "hard" definition that fluctuation is not allowed.

Some texts employ the "soft" definition in connection with entropy. Consider, for example, the textbook of Landau and Lifshitz /9, p. 350/, where the theory of fluctuations is based on the fluctuation of entropy of an isolated system. However, the treatment can be revised into a form which is not based on the fluctuation of the entropy of the isolated system.

Another example is figure 11-9 of the textbook by Alonso and Finn /6, p. 476/. The figure presents the "variation of entropy of an isolated system while the system is evolving toward equilibrium". According to the "hard" definition the entropy of an isolated system increases monotonically and has a constant value at equilibrium.



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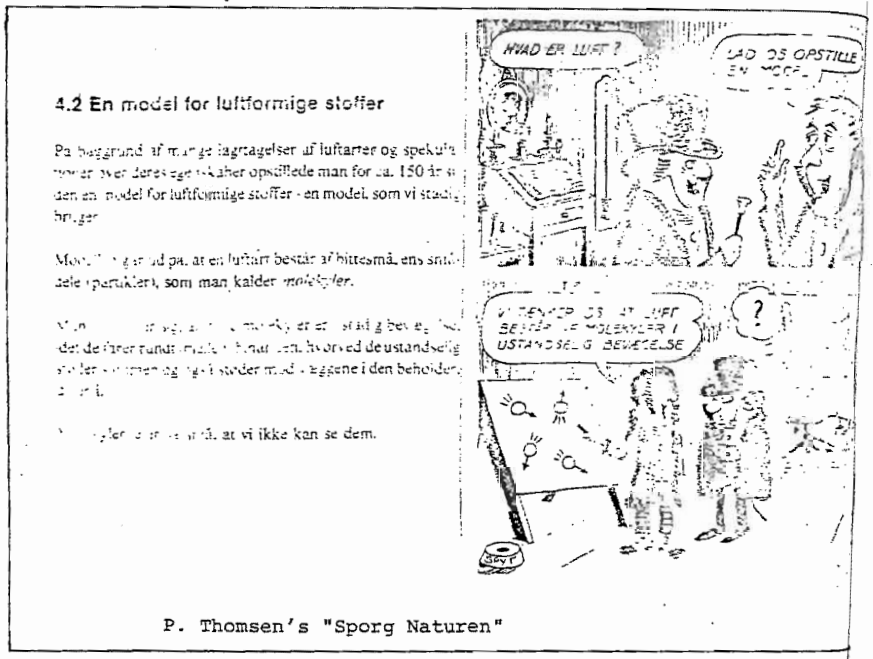

4.2 En model for luftformige stoffer
HVAD ER LUFT ?
LAD OS OPSTILLE EN
VI TÆNKER OS AT LUFT BESTÅR AF MOLEKYLER I USTANDSELIG BEVÆGELSE
?
SPYT

P. Thomsen's "Sporg Naturen"

SOME EXPERIMENTS AND ARGUMENTS FOR QUANTITATIVE DETERMINATION OF ENERGY DEVALUATION

U. Backhaus, H.J. Schlichting
University of Osnabrück

The experiments described here, have been presented in order to show how one can develop the qualitativ concept of energy degradation to yield quantitativ expressions and simple measuring proceedings.Therefore, the purpose of this paper is not to present new or interesting experiments but to illustrate and clarify our conception for introducing entropy resp. exergy, the basic ideas of which are shortly summarized in the following (for more details see the contribution of Schlichting/Backhaus in these proceedings):

- No spontaneous processes run backwards by themselves (i.e. they are irreversible). Therefore such processes are connected with energy devaluation because after their running down the systems involved can be used for less purposes (priciple of energy degradation).
- Friction, heat conduction and chemical reactions are typical examples for energy devaluating processes.
- At first sight, many natural events contradict the above mentioned priciple, e.g. temperature differences arise spontaneously or chemical reactions run opposite to their natural direction. However, in all such cases there is at the same time at least one process running down in its natural direction. Therefore, the latter process may be conceived as driving the former backwards.
- Of two processes that one is connected with a greater energy devaluation, which is capable of driving the other one backwards.
- In order to get quantitative results the total energy devaluation ΔV_c of a composed process is defined to be the sum of the devaluations ΔV_1 and ΔV_2 due to the partial processes:

$$\Delta V_c = \Delta V_1 + \Delta V_2 \quad \text{(additivity)}$$

- By this it is possible to determine the ratio $\Delta V_1/\Delta V_2$ due to two

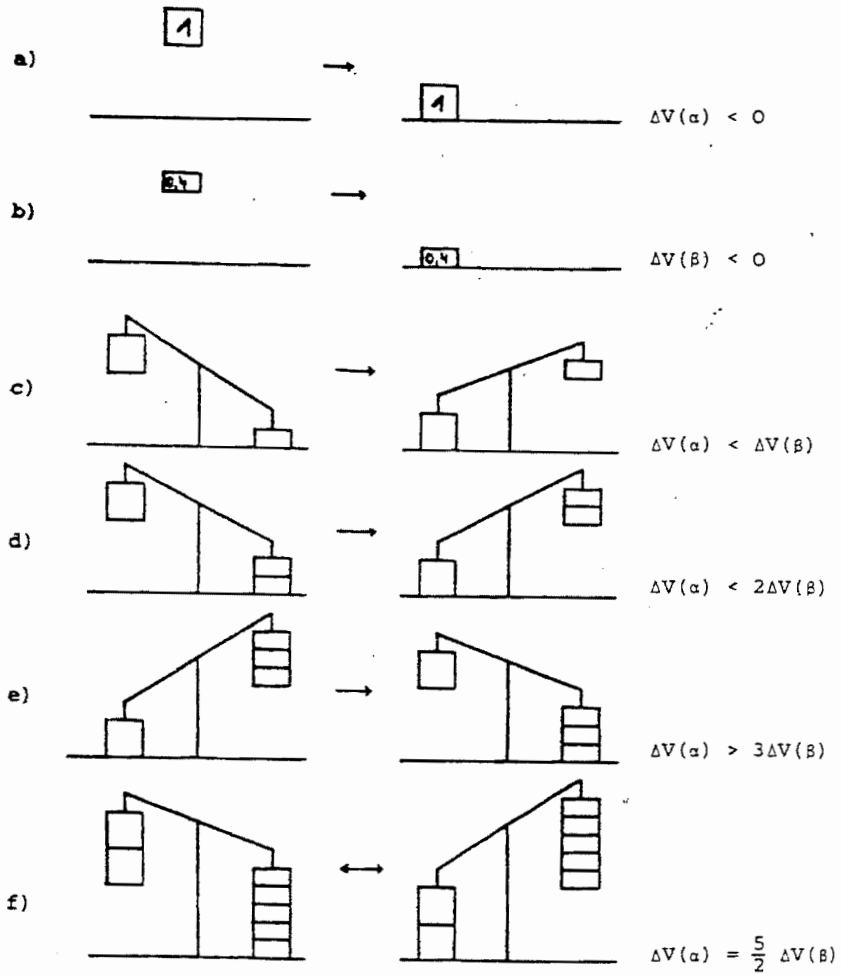


Abb. 1: Quantitative comparison of the energy devaluations due to two processes of the kind "dissipation of mechanical energy at constant temperature"

processes, in principle with arbitrary exactness as illustrated in the following examples.

1. (Isothermal) Dissipation processes

Two processes α and β of the kind "Falling down (and staying at rest) of a weight" differ only in the masses of the weights: $m_\alpha/m_\beta = \frac{5}{2}$.

- Both processes are obviously irreversible and therefore connected with energy degradation (Abb. 1 a,b)[1]

$$\Delta V(\alpha) < 0, \quad \Delta V(\beta) < 0 .$$

- By means of a lever, one can show that α is capable of driving β backwards (Abb. 1 c):

$$|\Delta V(\alpha)| > |\Delta V(\beta)| \Leftrightarrow \Delta V(\alpha) < \Delta V(\beta).$$

- Further experiments render more and more precise estimations possible (Abb. 1 d-f) with the final result that two processes of the type α reverse five processes of the type β and vice versa.

$$2\Delta V(\alpha) = 5\Delta V(\beta) \Leftrightarrow \frac{\Delta V(\alpha)}{\Delta V(\beta)} = \frac{5}{2} = \frac{m_\alpha}{m_\beta} = \frac{\Delta E(\alpha)}{\Delta E(\beta)} \Leftrightarrow \Delta V \sim \Delta E \qquad (1)$$

The energy degradation due to processes of the mentioned kind is proportional to the "lost" mechanical energy or, the other way round, proportional to the maximum of mechanical energy "available" from the process (for instance by using it to lift another weight up).

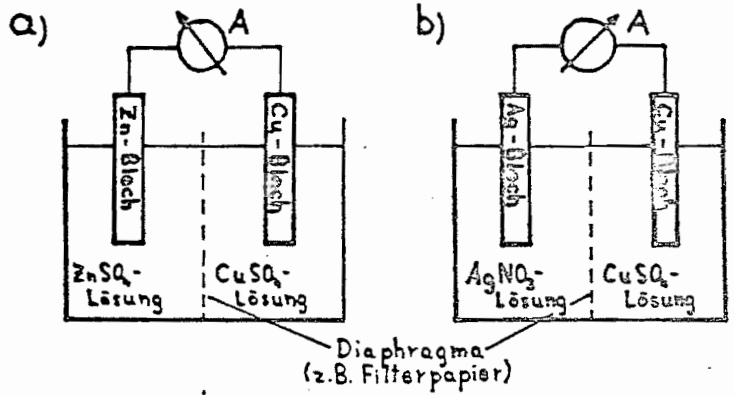
- It can be proved that the constant in equ. (1) is proportional to the inverse thermodynamic temperature (an outline of the proof is given in the contribution of Schlichting/Backhaus):

$$\Delta V \sim \frac{\Delta E}{T} \qquad (1')$$

2. (Isothermal) Chemical reactions

In order to compare the energy devaluations due to the following reactions quantitatively

1 ΔV stands for value change. Therefore, an energy devaluation is characterized by ΔV < 0.



$$Zn \rightarrow Zn^{++} + 2e \;\big|\; Cu^{++} + 2e \rightarrow Cu \quad 2Ag^{+} + 2e \rightarrow 2Ag \;\big|\; Cu \rightarrow Cu^{++} + 2e$$

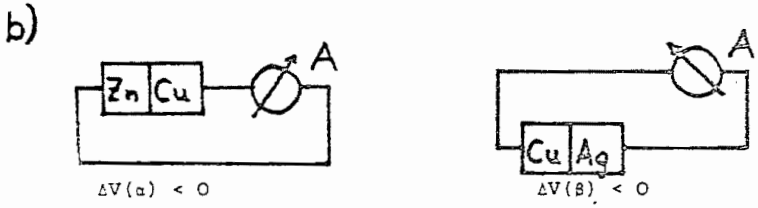


Abb 2: a) Reactions α and β run down in electrochemical elements. The deflection of the amperemeter symbolizes the direction of the electric current.

b) Symbolic figuration of the galvanic elements.

$$\alpha: \; CuSO_4 + Zn \rightarrow Cu + ZnSO_4$$

$$\beta: \; 2AgNO_3 + Cu \rightarrow 2Ag + Cu(NO_3)_2$$

they are driven in so called galvanic elements (Abb. 2) thus forcing the exchanged electrons to detour through an amperemeter or a little motor[2].

- The sign of the electric current shows the direction in which the reaction is running (Abb. 2).

2 The corresponding experiments may be done for instance with the "Elektrochemie-Arbeitsplatz" selled by LEHRMITTELBAU MAEY/LEYBOLD, which is suitable for pupils experiments.

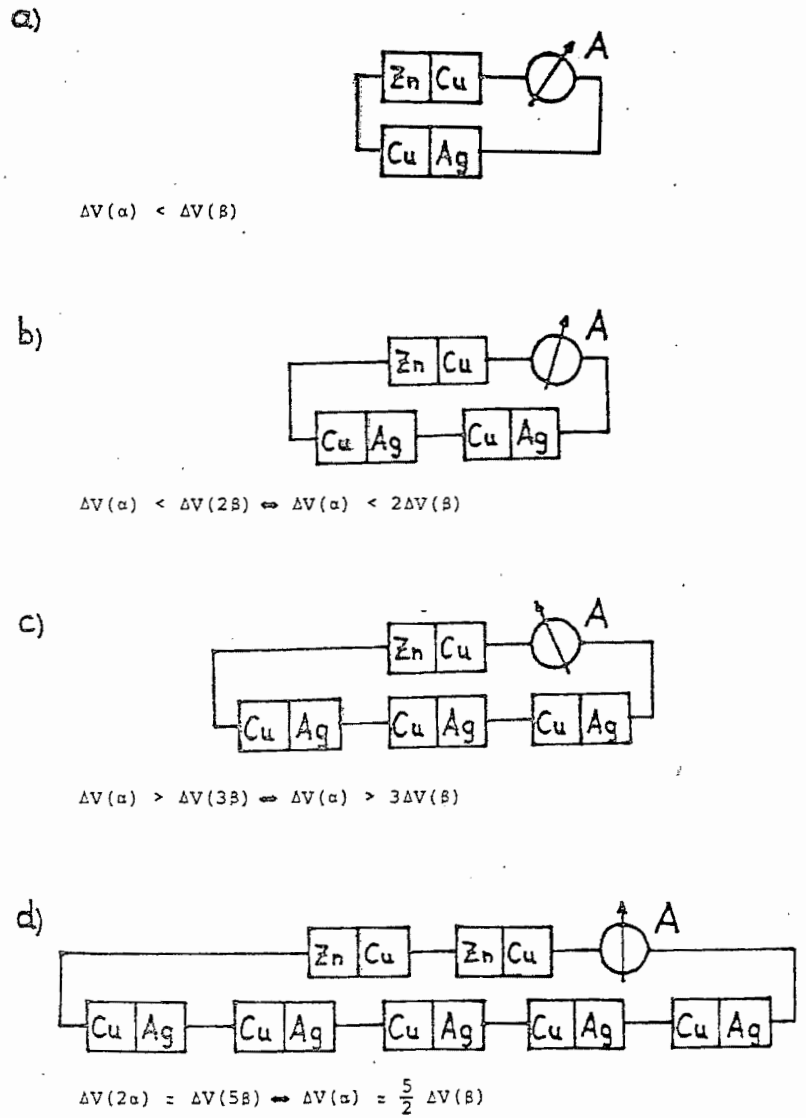


Abb. 3: Quantitative comparison of the energy devaluations due to electrochemical reactions

- Integrating both elements within a single electric circuit so that both oxydation sides are connected (Abb. 3 a) one gets an electric current whose direction indicates α running down in its natural direction and β opposite to it. Therefore, α is capable of driving β backwards:

$$|\Delta V(\alpha)| > |\Delta V(\beta)|.$$

- Experiments very similar to those mentioned above (compare Abb. 1 c-f and Abb. 3 a-d) prove that the reduction of two mols of Cu^{++} by means of zinc (i.e. 2α) is capable of driving the reduction of ten mols of Ag^{+} by means of copper (i.e. 5β) backwards and vice versa:

$$2\Delta V(\alpha) \simeq 5\Delta V(\beta) \Leftrightarrow \Delta V(\alpha)/\Delta V(\beta) \simeq \frac{5}{2}.$$

- The finally reached equilibrium is characterized by vanishing electric current: the electromotoric forces ε of the connected elements are mutual compensating. That means:

$$\Delta V(\alpha)/\Delta V(\beta) = \varepsilon(\alpha)/\varepsilon(\beta) \Leftrightarrow \Delta V - \varepsilon.$$

Therefore, the EMF ε of a galvanic element is a measure of the energy devaluation due to the corresponding chemical reaction.

- Because of the additivity, the energy devaluation is proportional to the transposed number of mols and therefore, to the maximum of electric work W_{max} being done by the corresponding reaction.

$$\frac{\Delta V(\alpha)}{\Delta V(\beta)} = \frac{\varepsilon_\alpha}{\varepsilon_\beta} = \frac{W_{max}(\alpha)}{W_{max}(\beta)} \Leftrightarrow \Delta V - W_{max} \qquad (2)$$

- Like in the case of dissipation processes, the concept of energy devaluation based on the capability of processes of reversing othe ones has been proved to be a measure of the maximum of mechanical energy, "available" from the process. It is easy to show that the constants in (1) and (2) are the same. So the result is again

$$V - \frac{W_{max}}{T} \qquad (2')$$

- Further arguments taking the caloric effect of the mentioned reactions into consideration (Backhaus, U., Schlichting, H.J.: The concept of energy devaluation as a link between physics and chemistry to be published) yield the well-known result

$$\Delta S = (\Delta H - \Delta G)/T,$$

were ΔH and ΔG are the changes of enthalpy and Gibbs free energy re-
spectively. So the considerations turn out to be a suitable entra

GUIDING THOUGHTS FOR TEACHING THERMODYNAMICS

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According to our nomenclature such phenomena whose course may be reserved at any moment are called reversible phenomena. In other words they may happen the other way without any additional processes. However, most of the physical phenomena are irreversible. It is obvious that some processes occur easily in one direction, but to reverse their course a number of additional processes, which are not encountered in the primary phenomenon, are required.

It is helpful in teaching thermodynamics to distinguish between natural and artifical physical phenomena. If a phenomenon, a process is natural, its reversal is artificial. According to Max Planck natural phenomena occur by themselves, without any intervention or influence of man, e.g. the flow of heat from a body at a high temperature to a body at a low temperature, the production of heat by friction, diffusion and so on. Artificial processes are always possible, but they do not occur by themselves. They are possible on condition that they are accompanied by natural processes. One of such artificial phenomena is the conversion of heat into mechanical work. In a heat engine the artificial process of coverting heat into mechanical work is accompanied by a natural heat transfer from body at a higher temperature to a body at a lower temperature. Any natural change of state is a transfer from a less probable state to a more probable state. Of all the possible motions the thermal motion is the most probable. The fact that the phenomena in the world comply with certain quantitative laws is called the first law of thermodynamics. The awareness that events in the world develop in a certain direction makes the second law. The concept of entropy is used to state the second law of thermodynamics in a different way. In the advanced treatment of thermodynamic processes there occurs a quantity, now relating energy to absolute temperature, now associated with the probability of a given distribution of momentum among molecules, and again expressing the degree in which the energy of a system has ceased to be available energy. Its form suggests that these are all aspects of a single physical magnitude. Application of the second law of thermodynamics leads to the conclusion that if any physical system is left to itself and allowed to distribute its energy in its own way, it always does so in a manner such that this quantity called entropy increases, while at the same time the available energy diminishes.

CAN CHILDREN UNDERSTAND ENTROPY?

Report of WORKSHOP A, on conceptual problems children may encounter in three different teaching approaches to Entropy

led by Joan Bliss
Chelsea College, University of London

Introduction

This paper has three main parts: the first deals with what happened in the workshop itself; the second gives a summary of the participants' written accounts of what research they would like to see taking place as a result of the workshop; the third is a bibliography of research that has been done in areas related to Entropy and the 2nd Law. The first part is based on my own notes and an excellent set of notes made for the workshop by J.W.R. Fennema and also on some notes by Joachim Schlichting on his own presentation. Renders Duit forwarded a very complete bibliography and I have just added a few other references. (I would like to thank these three people for their assistance.) In the paper I have tried to give a general picture of what happened in the workshop without entering into the detail of all participants' contributions.

1.1 The Workshop

Given the theme of the conference 'Entropy', two problems confronted the workshop immediately. Firstly, there is not a great deal of research in the area of children's ideas about thermodynamics, Entropy and the 2nd Law, although there are some interesting findings in related areas such as children's ideas about energy and work. Secondly there was no consensus among the participants of the workshop as to the most appropriate way of teaching the 2nd Law, it was, therefore, not possible to agree easily on what set of conceptual ideas would be involved for children learning this topic.

It was agreed that three approaches to the teaching of the 2nd Law, each sufficiently different - it was hoped - from the others, should be chosen. Each approach would be presented to the workshop with a view to analysing what were thought to be key underlying concepts that children might have difficulty in tackling and where possibly the

child's intuitive understanding of the concept might be very different from that of the teacher's. Each presentation had a discussant whose job was to comment on, or to take further the analysis and to open the discussion to workshop participants. In this section each approach is presented briefly and is followed by a commentary summarising generally both the discussant's ideas and also ideas and questions arising from workshop participants.

Prior to the first presentation, Louis Timbal, Paris, reported on a study by Professor Pelicier, Head of Psychotherapy at the Hospital Necker, Paris, on how the notion of energy is seen through publicity. The main finding was that 'body energy' is seen as natural energy whereas other sources of energy are seen as artificial. Many questions were raised about this particularly as to the purpose of the advertising, as to how the natural image of energy was related to ecological and other crises, and whether or not such an image relates to anything that is taught in school.

Some participants suggested this inquiry provided a good starting point for further research in school, the following topics were put forward:

- How do teachers talk about mechanical energy?
- Does teaching, related to the human body and energy, have much more meaning to children than other forms of teaching about energy?
- Should teaching about energy envisage some area in between the concrete and the abstract to do with the energy of machines, such as motor bikes, where such machines are real objects more closely related to young people than power stations, etc.

Approach No. 1 (presented by Joachim Schlichting)

Evaluation of pupils' reasoning during the teaching of energy conservation (1st Law) showed two important and contradictory aspects. Firstly, energy conservation seemed to be understood but only formally and the ideas could be applied in simple but somewhat artificial experimental situations. Secondly these same pupils failed to use these ideas in everyday life experience. Pupils'

description of these experiences was dominated by ideas of 'consumption', 'using up', 'devaluation', for example:

"Clean water gets spoiled in being used for household chores".

"Fuel tanks and batteries become empty or used up".

"Rooms in houses cool down when the heating is not functioning".

"Clothes wear out".

It was thought important, however, to try and retain the notion of energy conservation within the physics syllabus and yet attempt to translate the notion of 'consumption' into reasonable teaching material so as to avoid the inherent contradiction between conservation and consumption. Children's initial reactions to this seemed to show that they could envisage without too much difficulty that things were 'consumed' or 'degraded' in their quality and yet conserved quantitatively at the same time. For example, sand castles are built, and are later destroyed by people or tides, but the sand remains. Two key ideas emerged:

- development of the concept of energy devaluation which would account for that class of experiences of devaluation encountered by children, without giving up the energy conservation principle
- later generalisation of this idea of devaluation so as to lead to a physical quantity, entropy or exergy.

In order to teach the concept of energy devaluation, pupils have to be introduced to various kinds of processes. Firstly there are processes which run down by themselves without effecting anything else (spontaneously), these are similar to children's ideas about devaluation. There are other processes which run in the reverse direction (e.g. water getting hot 'revaluation') which can be reconciled with this principle of energy devaluation by arguing that the reversing of a spontaneous process may be conceived of as being driven down by another spontaneous process running in its natural direction. The revaluation of the first process is compensated by the devaluation of the second. Thus the central concept is that energy revaluations are driven by energy devaluations.

General Discussion (Discussant - Paul Black)

It might be asked do children really want to think about or draw conclusions from their everyday experience? Do children in any way see such experience as problematic? Is not the everydayworld just as it is, why should there be a need to question it? Also why should there be a need to relate the rather disparate but ordinary things that happen? For example, why should knocking down sand castles or eating food have anything in common?

If everday experiences are to be used then the choice of the examples is problematic. Some examples can be confusing, others just not interesting or trivial, while some others are just too difficult to grasp. Examples will probably need an element of surprise to appeal to children and will also need to answer the problem that the child, not the teacher, is asking.

Although the notion of devaluation may be close to children's experiences in order for them to reach an understanding of the 2nd Law, the concept of revaluation must be introduced as an integral part of the former concept and with the two concepts necessarily, although somewhat loosely linked. These two concepts would also involve the notion of direction which would have to be tied in with them. The understanding of these three ideas and the linking them together is probably more difficult than anticipated, even at a purely qualitative level; the choice of examples here would also be crucial.

It was also remarked that the 'ongoing development' in the bio-sphere and the 'downgoing development' as far as concerns the approach to equilibrium in physics and chemistry may not be 'conflicting' for children. For adults the 'conflict' arises from an abstraction that perhaps children are not likely to make.

Several participants remarked that they were very struck by the ideas that the teaching of Entropy may introduce children to a particularly pessimistic view of the world as expressed by Peter Atkins in his phrase "The deep structure of change is decay". Participants wondered whether or not children experienced or encountered this notion of pessimism and it was thought to be worthwhile following up.

It was thought that although perhaps this strategy for teaching of Entropy was interesting, a great deal however would depend on the actual tactics used in carrying it out.

Approach No. 2 (Presented by Matilde Vincentini)

In trying to think about an approach to the teaching of thermodynamics it was important to see that one of the more conceptually demanding tasks for children is to see the relationships between concepts, thus a central idea would be that of 'system' and how elements of the system interact with each other. The description of the system generally requires 4 categories of variables, energy of parts variable, a co-ordination or aggregation variable, a mass or volume variable, and a time variable. Usually, however, the theory of thermodynamics leaves the time variable implicit.

A second important idea is about how processes can be 'forbidden' and what constitutes a process. Yet another conceptually demanding task for children is how to describe change, either changes which happen spontaneously or non-spontaneously. What is a spontaneous change, is in itself a question because of the notion of interaction.

A third crucial idea in the teaching of thermodynamics is the zero-principle 'everything in the environment is at the same temperature'.

Two questions follow from the above:
How can we describe macroscopic systems/objects and their changes?
Why is a system/object changing? Spontaneously or because of influences from the environment?

Discussion (Discussant F. Hermann)

It was thought that children will have difficulty with the notion of a system, and would often tend to see a system as a 'thing', the notion being too abstract. Also the notion of system is introduced to children in school as an isolated system.

Many participants were extremely worried about bringing such a formal, axiomatic approach to children and that such a method would suppress various

ideas that children might have. Also added to this worry was the problem of the language used in such an approach. On the one hand there are those concepts or those words which represent the concepts which are invested with a real world meaning and not a scientific one, and there are other concepts where the language is so abstract that knowing the word does not in any sense help children.

With reference to the idea of temperature participants queried whether or not children would accept the notion of a 'plus infinity' without wondering whether or not there could be a 'minus infinity'.

Other notions that were seen to be conceptually difficult for children were: problem of homogenous system, the notion of an exchange between parts of a system, notions of heat and work, particularly with the colloquial use of work.

Approach No. 3 (Presented by Alfred Pflug)

It was thought that the approach to Entropy should initially be a qualitative one. In some ways the 2nd Law was trivial for children. Stones fall, things get broken and rot away, etc. But there are contradictions so, for example, "Why doesn't the sky fall on our heads?" (as one of the characters of the 'Asterix' cartoon asks); children, plants and animals grow.

So the essential question is what is to be understood by order and disorder? Three kinds of disorder can be distinguished which are jokingly called: Disco, desk and Balaton disorder. Three types of disorder refer to kinetic chaos, configurational chaos and complete chaos respectively, that is, to chaotic motions, chaotic positions and to a chaos of both moments and positions.

In order for children to be able to cope with ideas like these it is important for phenomena to be localised. It is then necessary to ask what kind of principle is driving a system to order, and how it can be demonstrated that the creation of order on one spot entails the creation of disorder elsewhere.

Discussion (Discussant J.W. Monte Labor)

Most of the participants saw that the crucial concepts for children coping with these ideas would be those of order and disorder. Many views were voiced about how children would understand these ideas. Firstly, that problems of intention are very much involved in notions of order and disorder. Secondly, these two ideas are very much part of the life of young children in relation to their activity, but that a parent's view of order, disorder would be very different from that of an adults, as would one adult from another. Thirdly, is it sensible to talk about order and disorder? Is it not possible to think of such things in terms of the number of ways?

It was suggested that localisation of phenomena allowed the approach to move gently from a qualitative to a quantative approach, and so be more appropriate to school children.

1.2 Summary of Research Areas

Below is a summary of areas where workshop particpants would like to see research developed, or to know about already existing research:

Cognitive Areas:

Energy revaluation and devaluation

Energy degradation. Energy consumption

Notion of system. Notion of state

Notion of process and direction of process

Notions of order and disorder

General Areas:

What ideas children have about the problem of the 'energy crisis' and other such crises.

Does the teaching of the 2nd Law convey a pessimistic view of the world to pupils?

1.3 What Next?

At the end of the workshop it is necessary to face the question "Well, what does all this add up to?". Part of the problem with the teaching of Entropy and the 2nd Law is that most people in physics education,

and more particularly teachers themselves, are very aware of the difficulties this area will present to children. This awareness has led to a proliferation of different approaches to its teaching. Attempts at tackling the complexity of the notion of Entropy range from phenomenological approaches, which sometimes anchor ideas in the children's experience of the world, to imaginative and thoughtful choices of examples when using more quantifiable and statistical approaches. What is problematic about each new approach is that it introduces ideas of a new and different kind which may be equally as demanding to children as the original ones which were trying to be 'avoided' or 'bypassed'.

This like many other areas in science teaching - and education at large - suffers from the particularly formidable problem of why something is thought to be difficult to teach, this from both the teacher's and the pupil's point of view. From the teacher's point of view it would be sensible to have some sort of analysis of the conceptual demands of the key ideas involved in a given area and how it is taught (no notion should nor ever can be separated from the way it is presented.) What sort of model could be used to do such a job? Bloom's taxonomy has been used to look at examination questions; various authors in England (Shayer, Ingle) have attempted to use Piagetian stage to analyse the demands of particular parts of the science curriculum. These are beginnings and on the whole such analyses give only very general ideas. Also it should be said that the approaches to teaching Entropy differ so widely, that is, they are qualitatively so different, that there would be no one answer to a question such as how 'difficult' is the idea. However some attempt at this level of analysis might point out where such models are lacking and how they could be developed further to be more informative.

Secondly it is important to look at research on children's conceptions in the particular science notion in question. Such conceptions are based on a variety of sources: the children's experience, on what they have been taught, on the language they use, on general socially accepted ideas and myths, etc.; they are usually more than just 'common-sense' but in themselves constitute a sort of common sense. Quite often the children's representations have been considered as 'misconceptions' or

even have been thought of as 'wrong'. In as much as they do represent a pupil's perceptions of a given idea - regardless of their origin - it is important in teaching to find a way of 'taking them seriously' as they do constitute a vital part of the pupil's knowledge of the world. Unfortunately in the area of Entropy and the 2nd Law - as mentioned before - there is very little research, perhaps the workshop has underlined this particular problem.

2. Written comments of participants on the workshop

Many of the comments overlapped or were similar so I have attempted to form some general categories that cover most of what participants wrote.

2.1 General Areas

1. How is it possible to evaluate the different types of methods used by researchers so as to make better sense of the research findings?
2. Is it possible to get a picture of teachers' conceptions of or attitudes to the teaching of thermodynamics?
3. Is the notion of pessimism, so often connected with the 2nd Law, something that is creeping into the media? Or rather is the way in which the 2nd Law is seen to be talked about by scientists reflected by the non-scientist in the media in what could be seen as a pessimistic manner? Is this notion of pessimism possibly reflected in teaching?
4. What does a teacher do when faced with children's misconceptions (used in the sense of ideas different from those the teacher wants to teach) and how he or she organises teaching to take account of such ideas.

2.2 Ideas Related to Children's Representations

1. In some approaches to the teaching of the 2nd Law discrete variables are turned into continuous variables. In teaching it is usually believed that continuous variables are more difficult for children and teachers tend, therefore, to present items in terms of discontinuous ones. What makes sense from the pupil's point of view?
2. Some approaches to the 2nd Law use a macroscopic approach whereas others prefer a microscopic one. Have these approaches been analysed in terms of what ideas at either level are more conceptually difficult for children, and how easy or difficult is the passage from one to the other and which direction is preferable?
3. Which 'words' or the names given to ideas in science, are known to children in their everday language and what associations do these 'words' have with other ideas (similar to the work presented by Schaeffer)? Also what sorts of language do teachers use in presenting ideas? How aware are children of the difference between strictly defined science meanings and everyday meanings of words?
4. Importantly we need to know what makes a problem meaningful or interesting to children and beyond this what makes a set of problems have something meaningful in common.
5. What is needed to help children form generalisations out of a set of experiences? Perhaps more crucially, when these experiences are based on what is obvious, how can we get children to be interested in and attempt to understand what they take for granted?
6. Quite often varying the context of problems increases the interest and also makes greater generalisations possible but it also leads to a greater range of distractions, giving pupils a much harder task (possible conflicting frames of reference). What is known about this?
7. Problem of the objective versus the subjective. When science topics are presented objectively it is claimed that children cannot see the relevance of the topic and so are not interested. In order to counteract this many teaching schemes use a subjective approach building on children's experience and getting them involved. The problem however would seem to be that the more successful the subjective approach, the harder it is to make a transition to an objective approach and so the more confusion there can be in children's minds about the necessary distinction between these two dimensions. This is particularly the case in relation to the notion of order and disorder when reckoning by intention has to

give way to counting, and could be the case when focusing on body energy moving to more abstract ideas about energy.

8. Many participants requested further or new research on children's conceptions in various areas (see section 1.2).

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HISTORICAL APPROACH TO THERMODYNAMICS

Report of WORKSHOP B, led by G.Radnai
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Participants: Falk, Gottfried /Federal Republic of Germany/
Geszti, Tamás /Hungary/
Golab-Meyer, Zofia /Poland/
Gubanszky, Zenon /Poland/
Cai Huai-Xin /China/
Kolbenstvedt, Hans /Norway/
Nuvoli, Lidia /Italy/
Oblak, Seta /Yugoslavie/
Rogers, Eric /United Kingdom/
Vantsó, Erzsébet /Hungary/
Vironseppä, Atso /Finland/

Motivation

Brian Davis: The education and training of physics teachers-worldwide; Summary /p.9./

Another type of the intellectual isolation of physicists is hightlighted by the fact that fewer than 10% of correspondents mentioned the inclusion of the history, philosophy or sociology of science in teacher training courses.

Balatonfüred, 1981:

Piet Lijnse: Teaching Physics in a changing society /p.376./

If the scientific process comes into view it is always the so-called internal process that is emphasized and hardly anything about the external process /Project Physics/. It concerns the metodology of physics in its historical and philosophical context, as it is seen by physicists only.

Poul Thomsen: Teaching nuclear physics to all young people /p.157-158./

We should build on the knowledge our pupils have already achieved in a more unsystematic way by summarising and extending this knowledge...With this introduction we can ask the question:How did physicists find out? And the answer can be given in the form of historical survey,illustrated by a series of suitable experiments.

Jon Ogborn:Teaching about energy /p.331,335./

No wonder Robert Mayer's contemporaries /who did not see the unity in the diversity of Mayer's own examples/ thought him unsystematic, even crazy. More interestingly, his main line of argumet would strike many people today as peculiar, but has, I think something to teach us... /I am grateful to Yehuda Shadmi for making the issue so clear to me/...

Imagine a lesson which makes a careful study of a text by, say, Carnot, Rumford, Mayer or Joule. Could pupils see why there was a problem with caloric if they read Rumford asking how there could possibly be an endless supply of caloric got by squeering it from the atoms of a metal by the friction of a boring tool? Could they see the industrial revolution working in the mind of Carnot, as he tried to think quite generally about engines and machines?

George Marx: Our nuclear history /p.213, 214./

"Conserve energy!" - is printed on posters. -"But I have learned in the school that energy is conserved anyway" - may be asked by our clever pupils...The Second Law was discovered in the past century, when Industrial revolution became interested in constructing steam-engines. But formulating the law produced newer headaches elsewhere.

All participants agreed with the important role of the historical approach in teaching thermodynamics, but they emphasized the shortage of teaching time to deal with historical questions.

During discussion L.Nuvoli pointed out that the main problems connected with historical approach are that of school time organisation and training or retraining of teachers.Obviously it is not a problem easy to be solved because any introduction of new thematics or any change in approach implies courtailments and renouncements in different points of the programme.

Different suggestions arose to help the solution of the time-problem:

A.Vironseppä:In the text books we ought to have historical material what the pupils may read if they are interested. There are good examples at all over the world and also in Finland.

S.Oblak: In the second year of our language and sociology oriented high school we want to give to our pupils an image of physics through its history and through achievements and struggles of great physicists. Now the ratio between historical and pure physics is about 1:2 in this programme.

Gy.Radnai showed a series of posters which will be available for Hungarian schools in the next year. It containes pictures, photos about the main turning points of the history of Physics from 1450 till nowdays. The first poster showes the "live-strips" of more than a hundred scientists who lived in the mentioned period and whose names are more or less well known for the Hungarian secondary school pupils. The live-strips follow on each other visualizing the exponential growth of the number of scientists in time. On the other five posters 40% of pictures were chosen from a brilliant book: K.Simonyi "Cultural-history of Physics" which was published in Hungary in 1980 and its English and German translation has been preparing.

E.Vantsó added, that there is a great need for the background literature concerning the historical parts of science. She teaches adoults too and they enjoy the "stories". She mentioned the book Borec:"Monsieur Ampere" as a good example. This book was transleted from Czech into Hungarian and published last year in Hungary.

The participants of the workshop were asked to summarize the most important advantages and disadvantages of the historical approach. Their opinion reflects as the common beliefs of the physicists and physics-teachers as their own personal ideas, characters. It is worth to quote their sentences here, remarked that because English is generally not their mother language, they were obliged to simplify their sophisticated thoughts.

Advantages of the historical approach

H.Kolbenstvedt: Increase in motivation among the students. Pictures and posters as suggested by the workshop leader seem to be an excellent idea.

G.Falk: Demonstration of birth of an idea and its growth to one or more concepts /like quantities.../

E.Rogers: Shows those students who enjoy it how our concepts have been built and /sometimes/ tested.

T.Geszti: Historical digressions help to assess the importance of key ideas. Eliminating the plausible concept of caloric was an important historical point.

A. Vironseppä: Motivation: How did scientists get inspiration? How they worked? The historical approach helps to understand the original meaning of some technical terms too.

C.Huai-Xin: It is interesting. Helpful to develop student's thinking. Helpful to integrate natural and human sciences.

Z.Gubanski: Inspiration for doing the subject. It shows what kind of people made that branch of science. Historical approach helps in understanding /you are going step by step to higher levels of exactness/

S.Oblak: Our pupils will understand that finding the laws is not so easy. The historical approach in physics is particularly interesting for future non-scientists to comprehend the evolution of human mind and for pupils who are not the best in mathematics.

Z.Golab-Meyer: Physics teacher should study history of physics to understand the position of physics in science, in evolution /revolution/ of science, in technical revolution, in society , and to understand difficulties in formation of physical concepts. Only physics teacher can teach history of physics. Some historical "stories" can be very exciting for pupils /Galileo case, low temperature race, etc./ In some cases the historical approach can make the understanding more easy.

L.Huvoli: It offers various patterns of different types of modelling in organizing a theory. It shows that different theories, alternative or inclusing each other, can coexist in order to explain nature's proceeding at different levels. It offers a unique and not replaceable way to understand what it means to make science, what implies to take a scientific attitude.

Gy.Radnai: Social aspect: we can study the interaction between science and society. Personal aspect: we can learn to live together with our successes as well as with our failures either in learning or in teaching or in doing physics.

Disadvantages of the historical approach

E.Rogers: Some students dislike it and avoid learning and say: "it offers us a list of other people's mistakes". Too slow - loses attention.

G.Falk: If you would try the demonstration of birth of the ideas with all or even with many of the effective concepts in physics.

H.Kolbenstvedt: Takes too much time. Often more obscure and difficult. Many teachers are against historical approach.

A.Vironseppä: The physics courses are very hard, there is no time.

C.Huai Xin: Unecconomical in time. It can be used only occasionally.

S.Oblak: It takes very much time; we must take it from experimental work but in the first stage experimental work is

worth more. It has meaning only if we show also false lines of thought, mistakes not only successes, but it takes very much time. It does not help very much future technicians who must know more about the fundamental laws and their applications.

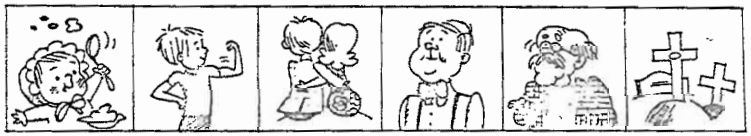
Z.Gubanski: It leaves not enough time for the most essential things.

Z.Golab-Meyer: Sometimes it obscures the subject...

T.Geszti: The incorrect explanations may stick to the memory of students. Developing parallel ideas instead of the correct one only needs much extra time.

E.Vantsó: Our pupils have to try to discover for themself the physics; it is the most important goal. If the historical approach does help to reach this goal: it is advantage, if it does not: it is disadvantage. In my opinion teachers have to mix different methods.

Gy. Radnai: Physics teachers are generally not experts in historical questions. Our traditional schoolbooks reflected the historical development of physics in the building of curricula: 1:mechanics, 2:heat, 3:light, 4:electricity, 5:atomphysics. In spite of it these textbooks di' not contain interesting historical texts. Nowdays, the new physics curricula do not follow the historical way. Just now has grown the responsibility of teachers for teaching historical approach.



BIOKEMIA

MICROCOMPUTERS IN PHYSICS EDUCATION

Report of WORKSHOP C, led by Esther Tóth

József Attila Grammar School, Budapest

There are two great domains of physics education where the arrival of microcomputers will produce essential changes. The computers will enable a deeper insight into the predictive Newtonian dynamics and into statistical phenomena than before. It is not only an improvement of the teaching possible but we can teach such consepts which more earlier hopeless high above the secondary school level. In this respect the Nuffield project played a pioneer role. Jon Ogborn elaborated an approach to statistical physics which is based on computer simulation of the energy distribution in solids. Different adaptations of this program created the greatest interest among the participants of the workshop. We present two simplified programs which can be run even on a small microcomputer like Sinclair ZX-81. Several other programs were presented, e.g. a videogame to introduce the concept of momentum (the original idea is due to Jon Ogborn) and an other one educating to thinking in bits (by F.Herrmann).

It is evident that the coming seminars on physics education have to devote considerable time to computer didactics.

Energy Distribution

```
1 Ø PRINT "HOW MANY ATOMS ARE IN THE SOLID?"
2 Ø INPUT A
3 Ø PRINT "HOW LARGE THE EXCITED ENERGY?"
4 Ø INPUT K
5 Ø PRINT "HOW MANY EXCITED ATOMS?"
6 Ø INPUT G
7 Ø DIM E(A)
```

```
8 Ø DIM N(2Ø)
```

Each of the G atoms has K quanta: N(K + 1) = G. The N(E) array starts from 1. There are atoms, however, which have ⌣ = Ø energy, so we need to transform the array variable (+1).

```
1ØØ LET N(K+1)=G
11Ø FOR I=1 TO G
12Ø PLOT 2 K, I
13Ø LET E(I)=K
14Ø NEXT I
```

The other atoms G + 1 to A has no energy.

```
15Ø LET N(1)=A-G
16Ø FOR I=1 TO A-G
17Ø PLOT Ø, I
18Ø LET E(I)=Ø
19Ø NEXT I
```

The random number X chooses an atom which looses one quantum. (If this atom has no energy, another X will be chosen.)

```
2ØØ LET X=1+(A*RND)
21Ø IF E(X)=Ø THEN GOTO 2ØØ
22Ø UNPLOT 2*E(X), N(E(X)+1)
23Ø LET N(E(X)+1)=N(E(X)+1)-1
24Ø LET E(X)=E(X)-1
25Ø LET N(E(X)+1)=N(E(X)+1)+1
26Ø PLOT 2*E(X), N(E(X)+1)
```

The random number Y chooses an atom which gets the previous quantum:


```
3ØØ LET Y=1+(A*RND)
31Ø UNPLOT 2*E(Y), N(E(Y)+1)
32Ø LET N(E(Y)+1)=N(E(Y)+1)-1
33Ø LET E(Y)=E(Y)+1
34Ø LET N(E(Y)+1)=N(E(Y)+1)+1
35Ø PLOT 2*E(Y), N(E(Y)+1)
36Ø GOTO 2ØØ
```

Random Walk

There are 20 sailors standing originally at the point X=20, Y=20.

```
1Ø FOR N=1 TO 2Ø
2Ø LET X(N)=2Ø
3Ø LET Y(N)=2Ø
4Ø NEXT N
5Ø PLOT 2Ø, 2Ø
6Ø LET T=Ø
```

The earlier places of the sailors are robed out. Random numbers decide about the directions of the steps made by the sailors. The new places of the sailors are indicated.

```
 7Ø FOR N=1 TO 2Ø
 8Ø UNPLOT X(N), Y(N)
 9Ø LET X(N)=X(N)+2*INT(2*RND)-1
1ØØ LET Y(N)=Y(N)+2*INT(2*RND)-1
11Ø PLOT X(N), Y(N)
12Ø NEXT N
```

The number of steps is counted too steps.

```
13Ø LET T=T+1
14Ø PRINT T
15Ø GOTO 7Ø
```

APPROACHES TO TEACHING THERMODYNAMICS

Report of WORKSHOP D, led by Jon Ogborn
Chelsea College, University of London

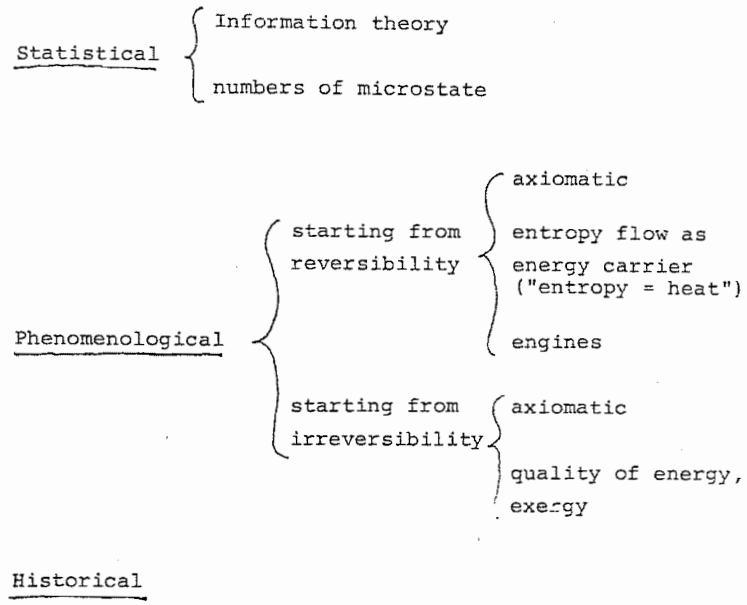
The group reviewed various approaches to the teaching of thermodynamics, and discussed their competing advantages and disadvantages. We saw a little profit in attempting to decide which would be "best", for several reasons:

- the value of any approach depends strongly on the aims of the teaching.
- the value of any approach depends on the age and previous knowledge of students.
- the value of any approach depends on the knowledge and experience of teachers.

It was therefore decided to attempt, instead to compare the properties of the different approaches.

Additionally, the group heard statements from partici-participants about matters that had not been sufficiently stressed in other parts of the Conference. It was reminded, by an example from a false interpretation of the Nernst Law current in many textbooks, of the dangers of error in statistical interpretations and of the long half-life of such errors, once established.The possibility of an axiomatic, phenomenological approach which nevertheless had an eye to the microscopic level was suggested, introducing entropy intuitively as a variable necessary a priori to account for coordination in a system composed of parts. The group was reminded of the importance of bearing in mind the competence of teachers, and of the significance of university teaching as the source of knowledge for teachers for 30 years after. Finally, the value of introducing ideas of chaos deriving from non-linearities was mentioned.

The various approaches were discussed in terms of the diagram below.



The importance, both in modern science, and for any understanding of the real world, of non-equilibrium thermodynamics, with order generated from disequil rium, was accepted, but there was no proposal to begin teaching in this way.

Discussion of the relative properties of statistical and phenomenological approaches led to the conclusion that a physics course whose aim and strucutre emphasised the particulate nature of matter would rather naturally adopt a statistical approach. This conclusion seemed inescapable for a chemistry course, or for a physics course closely coordinated with chemistry. While the difficulties of statistical theory were recognized, except perhaps for good mathematicians, the solution seemed to lie in simple games

with counters and dice, extended to microcomputer simulations. The view that quite young children could enjoy and learn from such games was supported. The pedagogic advantage of such concrete models implied however, an important need to give previous teaching about the nature of models, particularly models of atoms. This was felt to be both necessary, and good in itself as a part of physics teaching.

It was thought that the special property of phenomenological approaches of being model-free could be a pedagogical disadvantage, in that students could not be told what entropy "is". One view expressed was that the very fact that a good case could be made for calling entropy "heat" (in Carnot's sense) showed how easily phenomenological concepts could be confused. Against this, it was urged that an approach based on entropy as a substance-like quantity carrying energy (if taught in a frameweork of other conjugated pairs variables such as momentum flow and velocity, charge and potential) at least offered a concrete form of expression of relationship (the taxi!) which could be understood very early, and was very consistent with a relativistic quantum mechanical world-view. It was noted that this plan involved a drastic revision of much of physics teaching.

A scheme suggested to supplement the diagram was to regard teaching as progressing in stages:

(1) pictorial - whether with statistical games and models or entropy flows
(2) operative - practical calculation, usually essentially phenomenological
(3) theoretical - a fusion of (1) and (2) into an integrated scheme.

The comparison of information theory and "number of microstate" approaches within statistical approaches was briefly discussed. Recognising that there were as radical differences between them, and that both could be used, certain minor differences emerged. Informatic theory has the

advantage that information, in bits, is already a logarithmic quantity (thus avoiding the need to take logarithm) and has a clear interpretation (number of Yes/No questions). A possible disadvatage is the irrelevance to physics of many proposed initial examples, though this may change with the growth of computer science. In the number of microstates approach, great care is needed to simplify the mathematics, particularly by exploiting statistical games.

Within phenomenological approaches, proposals for an approach starting with the quality of energy, and using the exergy concept, had some discussion. Exergy, though 100 years old, is not well known except amongst engineers. Its great advantages is in being a kind of free energy with a zero referred to equilibrium with the environment, so being rather close to the intuitive, everyday idea of "energy" or "fuel". The approach could easily emphasize practical calculations of real importance, whether of heating for a house or the economy of a power station. By being based on the energy available from a state of eksequilibrium, it might be more consistent with modern non-equilibrium thermodynamics and with practical engineering. It was agreed, however, that much remained to be done before one could see how to develop a practical teaching programme.

In conclusion, it was felt that only time would tell which of the many competing approaches would survive, and that the urgent need is for various attempts to try them out. The statistical approach has at present the virtue of having been developed in detail and used on a large scale, even though only at ages 16-18 in the secondary school; with some preliminary work with younger pupils. It is important to try other approaches as well as to develop the statistical one: there is much to do and much to learn.

THE SOLUTION SEEMS TO LIE IN SIMPLE GAMES WITH COUNTERS AND DICE

Jon Ogborn

DECISION MAKING GAME

Report of WORKSHOP E, led by Henry Ellington
Gordon Institute of Technology, Aberdeen

This Workshop was based on the "Alternative Energy Project", a role-playing simulated case study that I and my colleague Eric Addinall produced for use in the AO-Level "Science in Society" course recently developed by the (UK) "Association for Science Education".

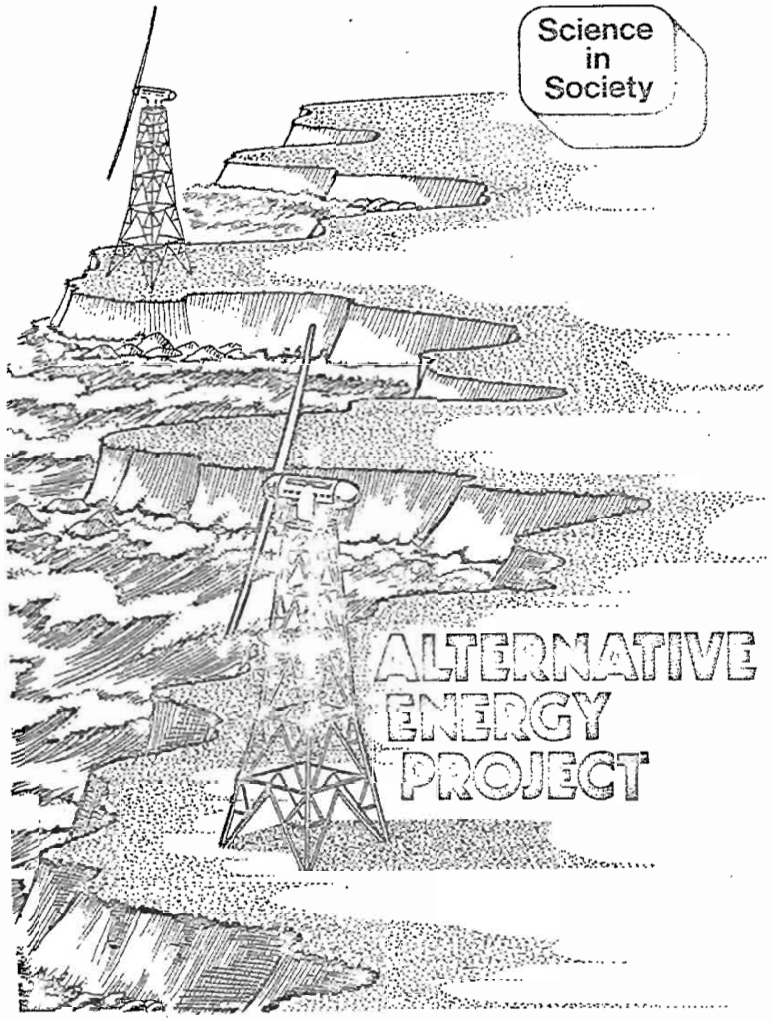
The exercise is designed to teach sixth-form pupils about the technical and economic feasibility of exploiting different alternative energy sources. It involves developing a 50-year rolling programme for meeting the future electricity requirements of the (imaginary) Island of Elaskay by making use of the island's indigenous energy resources - peat, solar power, wind power, tidal power and hydroelectric power - and consists of the following four stages:

- a preliminary 'taught lesson' on alternative energy, in which the pupils are introduced to the technological principles on which the various methods of generating electricity to be studied are based;
- investigation of the technical and economic feasibility of exploiting each of the five possible energy resources by the pupils, working in five separate cooperative groups, each of which examines one resource;
- a plenary session in which the five working groups first report on their findings to the rest of the class, which then draws up a rolling programme for meeting Elaskay's future electricity needs;
- a debriefing session, in which the lessons learned from the exercise are discussed.

At the Workshop, the participants were first introduced to the exercise, and were then guided through each of the above four stages, the educational aims of each stage being analysed and discussed as this was done. It was shown how the exercise provides an ideal vehicle for teaching about the conversion of energy from one form to another and for demonstrating some important real-life applications of the First and Second Laws, and how it also helps the pupils to develop communication and decision-making skills and socially-responsible attitudes. The Workshop ended with the participants having to devise their own rolling programme for meeting Elaskay's future electricity requirements, a task in which they succeeded admirably under the guidance of Barbara Hodgson, who took on the role of the "Chairperson of the Island Council".

For the benefit of those delegates who did not attend the Workshop and did not therefore receive the exercise documents, the 'student's book' is reproduced in full in these Proceedings. The full game package can be obtained from the Association for Science Education, Hatfield, Herts, AL10 9AA, England (price £3.00). Further information about the exercise, and the other science-based exercises developed by the author and his colleagues, can be obtained by writing to the following address:

Dr. Henry Ellington,
Educational Technology Unit
Robert Gordon's Institute of
Technology,
St. Andrew Street,
ABERDEEN AB1 1HG
Scotland


Science
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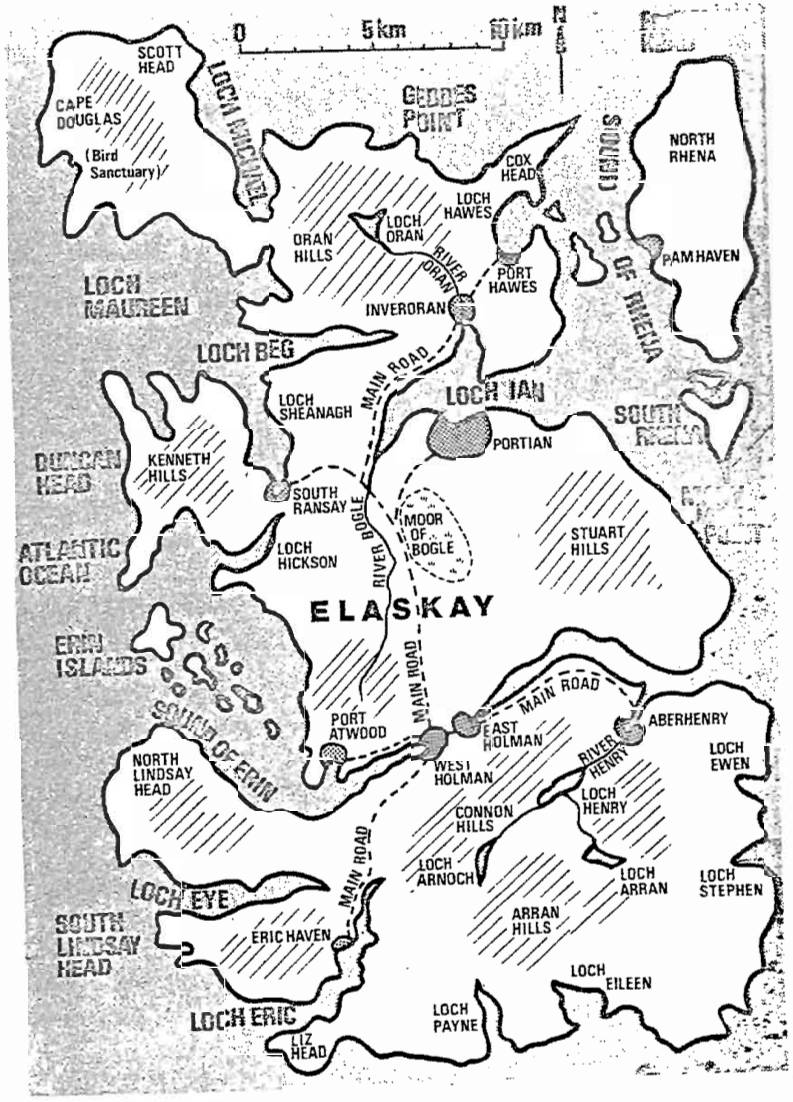
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LOCH ARRAN
LOCH STEPHEN
LOCH EYE
SOUTH LINDSAY HEAD
ERIC HAVEN
ARRAN HILLS
LOCH EILEEN
LOCH ERIC
LOCH PAYNE
LIZ HEAD

ALTERNATIVE ENERGY PROJECT

1. INTRODUCTION

Modern society is using energy – particularly in the form of electricity – at an ever-increasing rate. Some of our traditional sources of electrical energy (oil and natural gas) are rapidly becoming exhausted, and the large scale development of nuclear power (the logical replacement for these fossil fuels) is being held back because of political and environmental objections. We are therefore being forced to look for alternative methods of producing the electricity that we need. This project is concerned with some of these alternative sources of energy.

It is based on the imaginary Island of Elaskay, supposedly located somewhere off the West Coast of Scotland. The island has a population of 10 000. At the present time, it is served by diesel-powered electricity generators located in its main towns and villages. These have the ability to produce about 10 million units (kWh) of electricity per year, but the existing plant on Elaskay will become progressively inadequate over the next few years, with the situation becoming critical in ten years' time when the existing plant has to be shut down. The purpose of the project is to devise a programme for meeting Elaskay's electricity needs over the next 50 years, making full use of the island's natural energy resources. It is assumed that over the next 20 years, both the population and the demand for electricity will increase dramatically.

2. THE PROJECT

The class will be divided into five working groups. Each group will investigate the technical and economic feasibility of exploiting *one* of Elaskay's natural energy resources (peat, solar energy, *wind energy*, *tidal energy* and hydroelectric power). Detailed instructions plus all the necessary data are given on the following pages.

When the initial investigations are complete, there will be a session in which the five groups will report to the rest of the class on whether or not their method of generating electricity is possible.

In the final stage of the project, the class, working as a whole, will devise a programme for meeting Elaskay's future electricity needs, making the most effective use of its natural energy resources. This will have to meet the basic requirements set out below and will also have to be cost effective and environmentally acceptable.

	At present	In 10 years' time	In 20 years' time	Thereafter
Total annual electrical consumption (million units)	10	20	40	40

3. REVIEW OF ELASKAY'S ENERGY RESOURCES

The various possible energy resources from which electricity can be produced are either non-renewable resources (coal, oil, natural gas, peat, uranium) or renewable resources (solar energy, geothermal energy, wind energy, wave energy, tidal energy, hydropower).

For this project, several of these can be eliminated. It is not economic to use coal because of the absence of a local supply and the extremely high cost of transporting it to Elaskay. Oil is not feasible because of uncertainty of supply in the future. Natural gas is not feasible due to lack of a local supply. Uranium is not economic since the amount of electri-

city is too small to justify the cost, and there are also political and environmental objections. Geothermal energy is not feasible due to lack of local geothermal sources. Wave energy is still at a comparatively early stage of development.

We are left with five possible sources of energy from which Elaskay's electricity requirements will have to be met over the next 50 years. These are *peat, solar energy, wind energy, tidal energy* and *hydropower*. You have the task of examining the feasibility of exploiting one of these resources by working through the appropriate section of this booklet.

Technology of peat-fired power stations

The technology of peat-fired power stations is well-established. Such stations are similar to coal and oil-fired stations in that the fuel is burned in a boiler house to raise steam, which is then used to drive turbines which in turn drive generators. The peat is cut from a convenient bog, transported to the power station, and dried before burning. To minimise transport costs, the station is generally built close to the source of supply.

A peat-fired power station produces a smaller amount of atmospheric pollution than a corresponding coal-fired station, but somewhat more than an oil-fired station.

A peat-fired power station would take roughly 2 years to build and would have a life of 25 years. It would have to be closed down or replaced after this time since it would become uneconomic to operate due to rapidly increasing maintenance costs.

Technology of solar power

The technology of power-producing solar cells was developed during the 1960s for use in the American and Russian space programmes. The most commonly used type of solar cell is manufactured out of a single crystal of silicon in the form of a flat slab. This can be used to produce power.

In a solar power station, the combined outputs of a large number of these cells is converted into high-voltage alternating current using special plant. It is then either fed directly into the grid system for immediate use or stored for future use by means of a hydro electric pumped storage scheme – see below.

A combined solar power/pumped storage scheme would take at least 5 years to build and would have an operational life of roughly 25 years. After this time, the solar cells would have to be replaced.

Technology of wind power

The underlying principle of wind power is simple: large windmills are used to extract energy from the wind and to drive generators. The windmills usually have two variable-pitch blades mounted at the top of a tall mast. The mounting contains the generator, and rotates in such a way as to keep the blades facing the direction from which the wind is blowing.

The electricity generated by such windmills is converted into high-voltage alternating current using special equipment, and is then either fed directly into the grid system for immediate use or stored for future use by means of a hydro-electric pumped storage scheme – see below.

The windmills used to produce electricity on a commercial scale are extremely large. They have to be spaced well apart for technical reasons (if sited too close together, they interfere with one another's wind flow). For environmental reasons they are usually spaced not less than a kilometre apart.

A combined windmill/pumped storage scheme would take roughly 3 years to build (the windmills themselves could be built in roughly 1 year, but the pumped storage scheme

4. PEAT-FIRED POWER STATION

Examination of technical feasibility of building a peat-fired station
Elaskay is fortunate in having a source of peat in the easily accessible Moor of Bogle 3 km south of Portian (see map). You may assume that a detailed survey has shown that the recoverable reserves of dried high-grade peat are of the order of 800 000 tonnes.

Let us now examine the feasibility of building peat-fired stations of the various sizes shown in row 1 of the Work Sheet opposite. The number of units of electricity that each would be expected to produce in a year is given in row 2, and the amounts of energy (MJ) that these figures represent are given in row 3. (1 kWh = 3.6 MJ).

But a peat-fired power station has an overall efficiency of 25%. So the amount of energy that each station would have to get from its peat supply each year is given in row 4. Since every tonne of peat contains roughly 9500 MJ of energy, we can calculate the number of tonnes of peat that each station would consume every year (row 5).

Use the figures for the annual fuel consumptions of the various stations to calculate the length of time for which Elaskay's recoverable reserves of 800 000 tonnes of peat would last if stations of different sizes were built (row 6).

Now assess the feasibility of building stations of different sizes, bearing in mind that a peat-fired station has an effective operational life of 25 years and it can only be justified economically if there is sufficient peat to keep it running throughout this period (row 7).

Examination of economic viability of building a peat-fired station
In this project, we will assume that it is the cost of the electricity produced which will largely decide which type of power station will be built. In order to calculate this figure for a peat-fired station, it is first necessary to know the costs of the station. These can be found as follows.

First, use the figures for capital cost per installed kW of generating capacity that are given in row 8 of your Work Sheet to calculate the capital cost of each station. (Note that the cost per installed kW falls as the size of the station increases; this is true for nearly all types of power station, and is one of the main reasons why Generating Boards generally build a few really big stations rather than a large number of small ones). Write down your answers to row 9.

A loan would have to be taken out to pay the full cost of building the station. Calculate the annual repayments on that loan, assuming that a low-interest loan is available such that the loan is repaid and the interest is covered by annual payments of £7.82 throughout the 25 year life of the station for every £100 borrowed (row 10).

Next, calculate the total annual cost of extracting, transporting and processing the peat needed to fuel the stations, assuming that every tonne used would cost £6 (row 11).

Finally, calculate the total annual costs (row 13) of the different stations by adding the annual repayments on capital cost (row 10), the annual extracting and processing costs (row 11) and the annual running and maintenance costs (row 12).

The cost per unit of electricity produced by the different stations (row 14) can now be obtained by dividing the total annual costs (row 13) by the annual electrical output (row 2).

would take considerably longer). Such a scheme could be expected to have an operational life of at least 50 years.

Technology of tidal power
The basic principle of tidal power is extremely simple. A barrage is constructed across the mouth of a suitable inlet or estuary in order to extract energy from the tidal flow by making the water flow through large turbines. Electricity can be generated from both the incoming and outgoing tidal flows. The simplest type of scheme is one in which only the outgoing flow is used. In this system, gates are opened when the tide is rising in order to fill the basin up to the high water level, and the water is then retained by closing the gates before the tide starts to fall. Once the external sea level has dropped sufficiently, the water is allowed to flow out of the basin through the turbines, which drive the generators to produce the electricity. With this so-called 'single effect' system, generation is limited to two comparatively short periods each day (roughly 3 hours per tide).

In order to make full use of the electricity generated by tidal power (which is not always produced at times of high demand) it is necessary to store the electrical energy using a hydroelectric pumped storage scheme – see below.

Apart from a slight modification to the ecology of the shore line of the basin, a tidal scheme appears to have no serious environmental drawbacks.

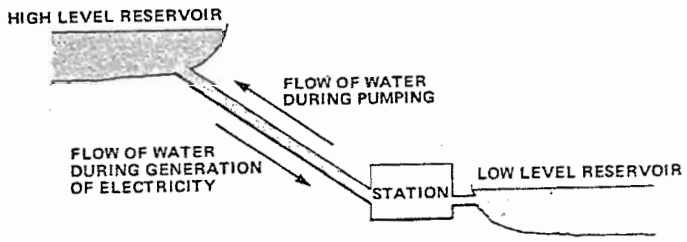
A combined tidal/pumped storage scheme would take roughly 4 years to build and would have an effective operational life of at least 50 years.

Technology of hydroelectric power stations
The technology of hydroelectric power generation is well established, such stations being in widespread use in many parts of the world. Water produced by natural rainfall is collected in a high-level reservoir. When it flows to a lower level, it drives a turbine, which in turn drives a generator which produces electricity.

The high-level reservoirs used in hydroelectric schemes generally have to be built in mountainous regions, often of high scenic and amenity value.

A hydroelectric power scheme would take roughly 3 years to build and would have an operational life of at least 50 years.

Pumped storage schemes
A pumped storage system would be essential if solar power, wind power or tidal power were to be exploited commercially on Elaskay. In such a scheme, electricity produced during times of low demand is used to pump water from a low-level to a high-level reservoir. During times of high demand, the water is used to generate electricity by allowing it to flow back to the low-level reservoir through a turbine which drives a generator.



WORK SHEET FOR PEAT POWER				
1. Size of station (MW)	5	10	15	20
2. Annual electrical output (million kWh units)	10	20	30	40
3. Amount of energy this represents (million MJ)	36	72	108	144
4. Amount of energy that has to be produced from combustion of fuel (million MJ)	144	288	432	576
5. Annual fuel consumption (tonnes)	15 100	30 300	45 400	60 600
6. Times for which fuel reserves would last (years)				
7. Feasibility of building station with operational life of 25 years (yes/marginal/no)				
8. Capital cost per installed kW (£)	600	550	525	500
9. Capital cost of building station (£ million)				
10. Annual repayments on capital cost (£)				
11. Annual cost of extracting, transporting and drying peat (£)				
12. Annual running and maintenance costs of station (£)	50 000	70 000	85 000	95 000
13. Total annual operating costs of station (£)				
14. Cost per unit of electricity generated (p)				

5. SOLAR POWER

The figures in row 1 on the Work Sheet show the annual electrical outputs of combined solar power/pumped storage schemes of different sizes. The annual electrical outputs of the solar power stations themselves will have to be larger than these, since the overall efficiency of the combined scheme is only 70%. Using this figure, calculate the number of units of electricity which need to be generated by the solar power station and note your answer in row 2.

If we assume that the station would use standard silicon solar cells of 4 cm^2 surface area, then each would have an average electrical output of 0.03 watts during the daylight hours (row 3). By assuming an average of 12 hours of daylight per day, the average number of units (kWh) of electricity that each cell would produce in a day has been calculated (row 4). From this has been found the average number of units that each cell would produce in a year (row 5). You can now calculate the number of solar cells that each size of station would require (row 6). This can be done by dividing the figures in row 2 by the annual output per cell.

Next, you should use the figures in row 6 to calculate the surface area of Elaskay that would have to be covered with solar cells in order to produce the various amounts of electricity given in row 1 (row 7). This can be done by assuming that each solar cell and its mounting requires 8 cm^2, a surface area twice that of the cell itself.

A solar power station of the type envisaged would require an associated pumped storage scheme so that all the electricity produced could be put to use. The sizes of the pumped storage schemes that would be needed for the different sizes of station are given in row 8. The only suitable location on Elaskay for a pumped storage scheme is in the Arran Hills (see map), where a scheme could be built using Loch Henry as the lower reservoir and Loch Arran as the upper reservoir.

Examination of economic viability of exploiting solar power on Elaskay

In this project, we will assume that it is the cost of the electricity produced which will largely decide which type of power station will be built. In order to calculate this figure for a solar power/pumped storage scheme, it is first necessary to know the costs of the scheme. These can be found as follows.

First, calculate the total capital cost of the cells and their mountings given that each cell costs roughly £3 (row 9). Note that this figure is unlikely to fall significantly in the foreseeable future, since the process of miniaturisation that has so dramatically reduced the price of so many electronic devices during the last decade is impossible in the case of solar cells. The output of such cells is directly proportional to their surface area, and they cannot, therefore, be made smaller without a corresponding drop in generating capacity. The cost will fall only if new types of solar cell are invented that can be manufactured more cheaply than present design.

The cost of conversion plant required for each size of station is given in row 10, and the costs of the associated pumped storage scheme are given in row 11. Find the overall capital costs of the scheme by adding rows 9, 10 and 11 (row 12).

A loan would have to be taken out to pay all the capital costs. Calculate the annual repayments on the loan, assuming that a low-interest loan is available such that the loan is repaid and the interest is covered by annual payments of £7.82 throughout the 25 year life of the station for every £100 borrowed (row 13).

Finally, calculate the total annual costs (row 15) of the different schemes by adding the figures for annual running and maintenance costs (row 14) to the annual repayments on capital (row 13).

The cost per unit of electricity produced by the different sizes of station (row 16) can now be obtained by dividing the total annual costs (row 15) by the annual electrical output (row 1).

WORK SHEET FOR SOLAR POWER					
1.	Total annual electrical output of scheme (million kWh)	10	20	30	40
2.	Total annual output of solar power station (million kWh)				
3.	Power output per cell (W)	0.03	0.03	0.03	0.03
4.	No. of units (kWh) of electricity produced per cell per day	0.00036	0.00036	0.00036	0.00036
5.	No. of units (kWh) of electricity produced per cell per year	0.1315	0.1315	0.1315	0.1315
6.	Number of cells required				
7.	Area required for solar station (m^2)				
8.	Size of pumped storage scheme (MW)	10	20	30	40
9.	Capital cost of cells and mountings				
10.	Capital cost of conversion plant (£ million)	1	1	3	4
11.	Capital cost of pumped storage scheme (£ million)	5.5	10.0	14.25	18.0
12.	Overall capital cost of solar/pumped storage scheme (£ million)				
13.	Annual repayments on capital (£ million)				
14.	Annual running and maintenance costs (£ million)	1.5	3	4.5	6
15.	Total annual operating costs (£ million)				
16.	Cost per unit of electricity produced				

6. WIND POWER

Examination of technical feasibility of exploiting wind power on Elaskay

The commercial exploitation of wind power is only feasible in places where the average wind speed is high (in excess of roughly 7 metres per second). Elaskay is fortunate in having three such sites, namely the westward-facing cliffs on Cape Douglas, Duncan Head and Lindsay Head (see map).

The sites all have high average wind speeds (see row 2 of the Work Sheet opposite), and the numbers of windmills they can accommodate is given in row 3. The average number of units (kWh) of electricity that each windmill could produce per annum is given in row 4. Note that the power output rises dramatically as the wind speed increases (it is in fact proportional to the cube of the wind speed).

Now calculate the total number of units of electricity that each site is capable of producing in a year (row 5).

A system of windmills would require an associated pumped storage scheme so that all the electricity produced is put to use. The sizes of the pumped storage schemes that would be needed for the different windmill schemes are given in row 6. The only suitable site for a pumped storage scheme is in the Arran Hills (see map), where a scheme could be built using Loch Henry as the lower reservoir and Loch Arran as the upper reservoir.

Examination of economic viability of exploiting wind power on Elaskay

In this project, we will assume that it is the cost of the electricity produced which will decide which type of power station will be built. In order to calculate this figure for a windmill/pumped storage scheme, it is first necessary to know the costs of the scheme. These can be found as follows.

First calculate the total capital cost of the windmills and their associated conversion plant for each scheme by making use of the fact that each windmill in the scheme will cost £200 000 (row 7).

Next, find the overall capital cost of each scheme (row 9) by adding the capital cost of the windmills and conversion plant to the capital costs of the associated pumped storage schemes (row 8).

A loan would have to be taken out to pay all the capital costs. Calculate the annual repayments on such a loan, assuming that a low-interest loan is available such that the loan is repaid and the interest is covered by annual payments of £7.82 over a period of 25 years for every £100 borrowed (row 10).

Finally, calculate the total annual costs (row 12) for each scheme by adding the figures for annual running and maintenance costs (row 11) to the annual repayments on capital (row 10).

The cost per unit of electricity produced by the different schemes (row 13) can now be obtained by dividing the total annual costs (row 12) by the annual electrical output (row 5).

WORK SHEET FOR WIND POWER				
1.	Site of scheme	Cape Douglas	Duncan Head	Lindsay Head
2.	Average wind speed (m/s)	11	9	8
3.	Number of windmills	8	9	9
4.	Number of units generated per year per windmill	777 000	400 000	254 000
5.	Total number of units generated per year by entire scheme (million units)			
6.	Size of pumped storage scheme required (MW)	2.3	1.4	1.0
7.	Capital cost of windmills and conversion plant (£ million)			
8.	Capital cost of pumped storage scheme (£ million)	1.61	1.8	0.8
9.	Total capital cost of scheme (£ million)			
10.	Annual repayments on capital (£)			
11.	Annual running and maintenance costs (£)	60 000	60 000	60 000
12.	Total annual operating costs (£)			
13.	Cost per unit of electricity generated (p)			

7. TIDAL POWER

Examination of technical feasibility of exploiting tidal power on Elaskay

The commercial exploitation of tidal power is only feasible in places where (a) the mean tidal range is high – roughly above 4 m, (b) there is a suitable basin with a relatively narrow mouth, and (c) construction of a tidal barrage would not interfere with shipping movements. On Elaskay, there are several sites which satisfy (a) and (b), but most of these have to be eliminated because of the fact that the basins contain ports (for example, Loch Eric and the Sound of Hourn).

Four suitable sites, have, however, been identified, namely Loch Hickson, Loch Eye, Loch Beg and Loch Payne (see map). Technical information about the schemes that could be built at these sites is given in rows 1 to 9 of the Work Sheet opposite. Note how the average number of units (kWh) of electricity that each scheme could produce per day (row 9) depends on the surface area of the basin (row 2) and the mean tidal range (row 3).

Use the number of units produced daily to calculate the total number of units that each scheme could produce per year (row 10).

A tidal power station would require an associated pumped storage scheme so that all the electricity produced could be put to use. The sizes of the pumped storage schemes that would be needed for the different schemes are given in row 11. The only suitable location on Elaskay for a pumped storage scheme is in the Arran Hills (see map), where a scheme could be built using Loch Henry as the lower reservoir and Loch Arran as the upper reservoir.

Examination of economic viability of exploiting tidal power on Elaskay

In this project, we will assume that it is the cost of the electricity produced which will largely decide which type of power station will be built. In order to calculate this figure for a tidal/pumped storage scheme, it is first necessary to know the costs of the scheme. These can be found as follows.

First, use the figures for capital cost per installed kW of generating capacity (given in row 12) to calculate the capital cost of each scheme (row 13). (Note that the cost per installed kW falls as the size of the station increases; this is true for nearly all types of power station, and is one of the main reasons why Generating Boards generally build a few really big stations rather than a large number of small ones).

Next, find the total capital cost of each scheme (row 15) by adding to the figures in row 13 the capital costs of the associated pumped storage schemes (given in row 14).

A loan would have to be taken out in order to pay all the costs for the different schemes. Calculate the annual repayments, assuming that a low-interest loan is available such that the loan is repaid and the interest is covered by annual payments of £7.82 over a period of 25 years for every £100 borrowed (row 16).

Finally, calculate the total annual costs (row 18) for each scheme by adding the figures for annual running and maintenance costs (row 7) to the annual repayments on capital (row 16).

The cost per unit of electricity produced by the different schemes (row 19) can now be obtained by dividing the total annual costs (row 18) by the annual electrical output (row 10).

WORK SHEET FOR TIDAL POWER				
1. Scheme at Loch:	Hickson	Eye	Beg	Payne
2. Surface area of basin (million m^2)	1.05	1.00	0.95	0.65
3. Mean tidal range (m)	9	10	9	6
4. Volume of water entering and leaving basin per tide (million m^3)	9.5	10.0	8.5	3.9
5. Usable volume V of water per tide (million m^3)	4.7	5.0	4.3	2.0
6. Effective operating head (m)	3	3.33	3	2
7. Energy generated per tide (MJ)	97 000	115 000	88 000	27 000
8. No. of units of electricity generated per tide	26 150	30 800	23 600	7 150
9. No. of units (kWh) of electricity generated per day	52 300	61 600	47 200	14 300
10. No. of units of electricity generated per year (million units)				
11. Size of pumped storage scheme required (MW)	9.0	10.6	8.1	2.5
12. Capital cost of scheme per installed kW of capacity (£)	775	750	800	925
13. Total capital cost of tidal scheme (£ million)				
14. Capital cost of pumped storage scheme (£ million)	4.95	5.83	4.47	1.75
15. Overall capital cost of tidal/pumped storage scheme (£ million)				
16. Annual repayments on capital (£ million)				
17. Annual running and maintenance costs (£ million)	0.10	0.10	0.10	0.07
18. Total annual operating costs (£ million)				
19. Cost per unit of electricity generated (p)				

8. HYDROELECTRIC POWER

Examination of technical feasibility of exploiting hydroelectric power on Elaskay

Elaskay has two hilly regions in which hydroelectric power schemes could be built, namely the Oran Hills in the North and the Connon-Arran Hills in the South (see map). The details are as follows.

Loch Oran Scheme: Upper reservoir – Loch Oran, with dam at SE end where River Oran leaves loch. Site of station – just north of Inveroran, discharging into River Oran at high water mark (River Oran is tidal in lower reaches).

Loch Arnoch Scheme: Upper reservoir – Loch Arnoch, with dam at NE end where River Henry leaves loch. Site of station – on SW corner of Loch Henry, discharging into Loch Henry.

Loch Arran Scheme: Upper reservoir – Loch Arran, with dam at NW end where river leaves loch. Site of station – on SE side of Loch Henry, discharging into Loch Henry near mouth of river. Note that the Loch Arran Scheme could either be developed as a straightforward hydroelectric power station or as a pumped storage system for use in conjunction with a solar, wind or tidal generating scheme.

Loch Henry Scheme: Upper reservoir – Loch Henry, with dam at NE end where River Henry leaves loch. Site of station – Aberhenry, discharging into mouth of River Henry.

Technical information about the schemes that could be built at each of the above sites is given in rows 1-6 of the Work Sheet opposite. Row 7 gives the maximum potential energy that one might expect to be released when the water flows from the upper reservoir to the lower level. Unfortunately, a hydroelectric power scheme has an overall efficiency of only about 65%. Given that 3.6 MJ = 1 kWh, calculate (row 8) the number of units (kWh) that each scheme could generate per year.

Finally, estimate the size of scheme (peak generating capacity) that each site could support. This can be done by assuming that a scheme can have 1 MW of peak generating capacity for every million kWh of electricity that it is capable of producing per annum, rounded down to the nearest million. Fill in your answers in row 9.

It is recommended that you check the answers obtained to the above calculations with your teacher before proceeding further.

Examination of economic viability of exploiting hydroelectric power on Elaskay

In this project, we will assume that it is the cost of the electricity produced which will largely decide which type of power station will be built. In order to calculate this figure for a hydroelectric power station, it is first necessary to know the costs of the station. These can be found as follows.

First, add the figures in rows 10, 11 and 12 to calculate the total capital cost of each scheme (row 13).

A loan would have to be taken out to pay for all the capital cost. Calculate the annual repayments, assuming that a low-interest loan is available such that the loan is repaid and the interest covered by annual payments of £7.82 over a period of 25 years for every £100 borrowed (row 14).

Finally, calculate the total annual operating costs of each scheme (row 16) by adding the annual running and maintenance costs (row 15) to the annual repayments on capital (row 14).

The cost per unit of electricity produced by the different schemes (row 17) can now be obtained by dividing the total annual costs (row 16) by the annual electrical output (row 8).

WORK SHEET FOR HYDROELECTRIC POWER				
1. Scheme at Loch:	Oran	Arnoch	Arran	Henry
2. Catchment area (million m^2)	9	10	14	44
3. Average annual rainfall (mm)	1400	1500	1500	1500
4. Altitude of reservoir above sea level (m)	150	250	270	130
5. Effective operating head h of scheme (m)	150	120	140	230
6. Mass M of water falling on catchment area per annum (million tonnes)	13	15	21	66
7. Change in potential energy of this water per annum (million MJ)	19	18	29	84
8. Number of kWh of electricity that scheme could generate per annum				
9. Peak generating capacity of scheme (MW)				
10. Estimated cost of dam (£ million)	0.5	0.4	0.6	0.7
11. Estimated cost of tunnel between upper reservoir and station (£ million)	1.0	1.2	1.6	3.2
12. Estimated cost of station and plant (£ million)	0.6	0.6	0.8	1.5
13. Total capital cost of scheme (£ million)				
14. Annual repayments on capital (£)				
15. Annual running and maintenance costs (£)	30 000	30 000	35 000	50 000
16. Total annual operating costs (£)				
17. Cost per unit of electricity produced (p)				

SCHOOL EXPERIMENTS FOR THE SECOND LAW

Report of WORKSHOP F, led by Csaba Sükösd

Dept. of Atomic Physics, Eötvös University, Budapest

The limited participation to this workshop is due to the fact that School experiments for the Second Law are either trivial or indirect, thus only few ideas were presented.

On one hand it is easy to say: "Look, a moving car stops besause of the friction, and if it left alone, it will never start again - this is due to the Second Law". You may say also while mixing a drink: "Look, the components of this drink will never separate again - this is due to the Second Law, too." Everyone may imagine thousands of such "experiments". This reasonment alone doesn't explain anything, it gives only an other name for irreversibility, which is already well known for the students from the everyday life.

On the other hand, experiments which aim to explain the cause of the irreversibility are hard to do, because of the knowledge needed in statistics. The first possible way for it are the dice-games (performed nowadays mainly with computers.) They are discussed elsewhere in details (worksh·· (Workshop).

At our workshop three contributions were presented.

1) Miss Esther Tóth (Hungary) showed a heat engine (Fig. 1) based on an idea of Prof. Delacote (France). The candle heats the water in the helical copper tube, which starts flowing upwards due to the density differences of the cool and hot water. On the bottom side of the floating disc the two ends of the tube are bent, so the streaming water makes the disk rotate.

If we start warming the water on which the disk is floating the rotation of the disk slows down. The rotation stops when the water starts boiling: if there is no temperature difference anymore, the heat engine cannot work.

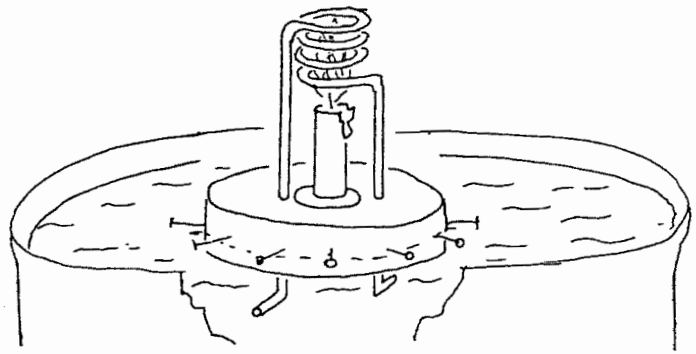


Figure 1.

This simple experiment can be performed by the pupils themselves. It may be helpful also in the case when the Second Law is tought in a fenomenological thermodynamics coarse.

2) Mr. Sokalski (Poland) showed a model experiment where the statistical approach to the concept of temperature and the Boltzmann distribution can be demonstrated on a quantitative way. The model consists of a vibrating horizontal membrane (for example monuted on a big loudspeaker)and a big number (N = 100) of indentical small aluminium bricks (dimensions: 4x7x10 mm). (Fig. 2). The bricks on the membrane can take three positions representing three different energy levels. This fine demonstration is described in an independent paper of this Proceedings volume.

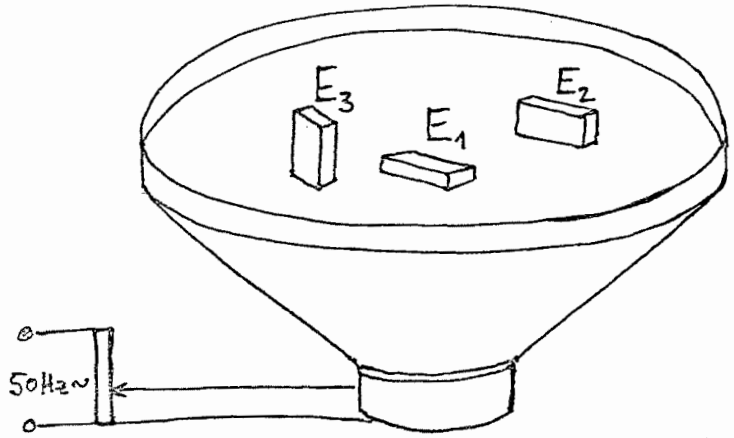


Figure 2.

3) Mr. Udo Backhaus (FRG) eluciated the entropy concept based on energy degradation. He used two chemical processes to make two batteries.

A:

$$CuSO_4 + Zn \rightarrow Cu + ZnSO_4, \quad \text{i.e.}$$

$$Cu^{2+} + Zn \rightarrow Zn^{2+} + Cu$$

B:

$$2\ AgNO_3 + Cu \rightarrow 2\ Ag + Cu(NO_3)_2, \quad \text{i.e.}$$

$$2\ Ag^{+} + Cu \rightarrow 2\ Ag + Cu^{2+}$$

Making these two batteries experimentally and switching them against each-other in a circuit we may conclude that battery A is "more irreversible" than battery B, because process A can drive process B backwards.

Similarly more precise quantitative statements can also be made about the "measure of irreversibilities". By the interpretation special care is needed to avoid the confusion between the electrical potential of a battery (this is an intensive parameter) and the "measure of irreversibility" (which should be an extensive one).

REPORT ON ROUND TABLE DISCUSSION OF THE NATIONAL POSTER REPORTS ABOUT TEACHING THE SECOND LAW IN DIFFERENT COUNTRIES

by Henry Ellington

Introduction

This round table discussion was held before lunch on the Friday of the conference, i.e. after most of the programme had been completed. It was chaired with great charm, firmness and skill by Poul Thomsen, who, in his opening remarks, began by saying that it was extremely gratifying to see that no less than four of the seven main speakers were schoolteachers. He then told the speakers that they had each been allocated a certain total time (which was slightly greater for those who had not yet spoken at the conference than for those who had), and that they could either use all of this up in their opening remarks or keep some in reserve for later. (This seems to me to be an excellent way of organising discussions of this type, and I hope that other chairmen will follow Poul Thomsen's example).

The speakers were then asked to address themselves to the following three questions, which therefore formed the framework on which the discussion was built:

Question 1 Should the Second Law of Thermodynamics be taught in secondary schools ?

Question 2 If yes, then why ? at what level ? in what way ?
If no, then why not ?

Question 3 What price would they be willing to pay for teaching the Second Law ?

Summaries of main presentations

1. Monte Labor (Sierra Leone)

The present situation in Sierra Leone is that both the First and Second Laws are taught in schools, at age 16-19. However, a recent survey showed that roughly 80% of the children did not appear to understand the connection between entropy and energy. Also, most children did not appreciate the wide-ranging applications of entropy; they felt that it was merely an abstract physical concept with no application to everyday life.

One possible way round the problem would be to drop the teaching of entropy from the school curriculum. This, however, would merely postpone the problem, and would (in the opinion of the speaker) be unfair to both pupils and teachers.

Another possible solution would be to retain entropy in the curriculum, but teach it in such a way that its applications to the 'real world' became clearer to the pupils, probably by employing some form of conceptual approach and making more extensive use of experimental work.

Clearly, the latter solution would have significant financial implications, since extensive re-training of teachers would have to take place. Also, the present syllabus would have to be re-written, with some topics being left out in order to make room for the new material. Nevertheless, the speaker felt that the changes would be worthwhile, since it would (in his opinion) be a tragedy if entropy were to be dropped from the school curriculum.

2. Silvano Sgrignoli (Italy)

The present situation in Italy is that the Second Law is taught in schools, but not entropy. Thus, the pupils have no understanding of entropy.

The speaker felt that the Second Law should be taught at school level, but that it was not necessary to teach entropy as such. He also felt that the methods of teaching thermodynamics could well be improved, and that an attempt should be made to teach both the applications of thermodynamics and the more abstract side of the subject. Clearly, this would be difficult, the challenge being to develop links between the two aspects of thermodynamics.

The speaker felt that one possible partial solution might be to teach exergy instead of (or before) entropy. This, he contended, would be simple to introduce, and could well help to provide the necessary links between the abstract side of thermodynamics and the applications of the subject to the real world. Such an approach could eventually lead on to the study of entropy by those students who actually needed it.

With regard to the price that would have to be paid for these changes, the speaker felt that it would be possible to make more room for thermodynamics in the curriculum by cutting down the amount of mechanics taught.

3. Eszter Tóth (Hungary)

This speaker firmly believed that the Second Law should be taught at school level, not merely to those who were to be engineers, physicists,

or chemists but to all future citizens. She felt that everyone should know something about the Second Law and its applications.

She felt that this teaching should take place at two distinct levels, namely, at 14+ and at 17+.

At the first level, roughly 4 - 6 lessons should be devoted to the subject, which should be treated in a qualitative manner, using very simple experiments and simulation-games to show how disorder increases in closed systems.

At the second level, a more sophisticated approach should be adopted, but this should again be based on the applications of the Second Law to real-life situations and problems.

She also felt that the Second Law should be incorporated into other aspects of science teaching, e.g. into teaching about the evolution of the universe.

4. Mathieu Römgens (The Netherlands)

This speaker felt that the Second Law should be taught to some pupils, but not to others.

In the Netherlands, all pupils study physics between the ages of 12 and 15, but the speaker felt that it was neither practicable nor necessary to teach the Second Law at this level, since (a) most of the pupils would not understand it, and (b) their time would be better spent studying topics (such as electricity and power generation) more relevant to their everyday lives.

In the case of the middle range of pupils who would be going on to study physics or some other branch of science at more advanced level, the speaker felt that it would be useful to give them a basic grounding in some of the more practical aspects of thermodynamics, teaching them about such topics as the maximum thermal efficiency of heat engines and the quality of energy.

Finally, in the case of the top 10% of pupils, he felt that thermodynamics should be taught at 'pre-academic' level, probably using some form of statistical approach, although this was not done in any depth at the moment.

With regard to possible problems, the speaker felt that these would mainly arise from the fact that the treatment of entropy in the physics class is, at the moment, different from that in the chemistry class. Clearly, it would take some time and effort to link the two approaches, and some re-training of teachers would also have to take place.

5. Magdalena Staszel (Poland)

This speaker expressed the view that one of the main purposes of physics teaching is to convince pupils that physics actually describes the world in which they live. It would therefore be a mistake not to teach the Second Law, since its applications are so widespread.

Such teaching should, she believed, take place at two levels.

At the lower end of the secondary school, the Second Law and its applications should be introduced in a qualitative manner ; entropy as an abstract quantity should not be introduced at this stage, however, since it would probably prove too difficult a concept for the pupils to grasp.

With older pupils, a more sophisticated, more abstract treatment could be adopted, preferably based on some form of statistical approach.

With regard to the price that would have to be paid for the introduction of this new material, the speaker felt that this could be kept to a minimum by re-organizing the curriculum in a more efficient manner; thus it would probably not be necessary to drop any of the existing syllabus material.

Clearly, some re-training of teachers would also have to take place, but the speaker felt that the associated problems could be greatly reduced by proper forward planning. In other words, teachers should be prepared for future curricular changes well in advance rather than at the actual time of the changes.

6. Fridrich Herrmann (Federal Republic of Germany)

This speaker was in no doubt that entropy should be taught at school level, giving two main reasons for his view :

(i) because it is such an important concept, and has applications in so many branches of physics;

(ii) because it is, in the opinion of himself and his colleagues the key "substance-like quality" that underlies the teaching

of thermodynamics. (The subject of "substance-like qualities" is discussed in some detail elsewhere in these Proceedings - see the papers by G. Falk and F. Herrmann).

With regard to the level at which entropy should be taught in schools, he believed that pupils should be introduced to the subject at age 10-11, and that further teaching should take place at ages 13-15 and 16+.

The speaker then outlined the way in which he felt that entropy should be taught at the middle level (13-15).

First, he felt that the idea of entropy as a "substance-like quality" should be stressed, rather than adopting a statistical approach.

Second, he felt that TS diagrams should be used rather than PV diagrams, since (he contended) children would find the former easier to understand. (Indeed, he later expressed the view that the concept of work should not be taught at all at school level.)

Third, he felt that information theory should be taught at the same time as entropy because of the close relationship between them.

7. Jon Ogborn (United Kingdom)

This speaker raised a number of important issues relating to teaching physics in general and thermodynamics and the Second Law in particular.

He began by criticizing the often-cited argument that we teach physics because it makes pupils "wise", claiming that it was doubtful whether such a claim could be substantiated. What we should do (he argued) is teach pupils what we know about physics, and then teach them that it should be used "for wise reasons".

He then addressed himself to the question of whether it is, in fact, possible to teach the Second Law and entropy effectively at school level. He pointed out that physics is taught successfully to only about 5% of the total school population, and that the success rate for thermodynamics is probably even less - not encouraging figures. Nevertheless, he felt that it was possible to achieve some level of success in teaching the Second Law, advocating an approach incorporating a statistical interpretation rather than one where no such interpretation is given. Teachers would, however, have to work very hard in order to achieve worthwhile results, and should not make the mistake of trying to achieve too much, since it is just as possible to fail to teach thermodynamics as it is to teach it successfully.

The speaker then turned to some of the problems associated with those who have to teach thermodynamics in schools. Many teachers (he contended) do not like teaching thermodynamics because they do not really understand it properly themselves, thus highlighting the need for suitable re-training. He also felt that such re-training could take place more effectively in a "mixed" educational system that is subject to "market forces" (as in the case in England) rather than in a centrally-planned educational system of the type

that exists in most Eastern European countries. With such central systems, any major change in the syllabus almost always makes it necessary to re-train large numbers of teachers - something that can cause problems.

The ensuing discussion

In the open discussion that followed the main presentations, a number of important issues were raised, and a number of fundamental differences of opinion became manifest.

Regarding the first (and, I think, key) question of whether the Second Law should in fact be taught at school level, the great majority of those who spoke seemed to think that it should.

Regarding the question of how it should be taught, the conference appeared to be divided into two opposing camps, namely those who advocated some sort of phenomenological approach and those who were in favour of a statistical approach. As I saw it, the former appeared to be in the majority.

Of the many speakers who contributed to the open discussion, I shall (at the risk of offending the others) limit myself to mentioning two.

The first is Eric Rogers, who made what was certainly the shortest contribution, which I shall quote verbatim:
"Every school should have a steam engine, and pupils should know how to make it work".

The second is George Marx, the man whose vision and drive made it possible for us all to be in Hungary and to enjoy what was without a doubt one of the most useful and stimulating conferences that it has ever been my pleasure to attend. He made the very telling point that it has taken over 100 years for us to learn how to teach Newton's Second Law in schools, so it would be unreasonable for us to expect to be able to teach the Second Law of Thermodynamics without going through a period of 'trial and error'. Nevertheless, he feels that the Second Law is so important that we must make every effort to ensure that both the scientists and the citizens of tomorrow have at least some appreciation of its wide-ranging implications. This, above else, is the message that I take away from Balatongyörök.

PROBABILITY IS THE MOST IMPORTANT CONCEPT OF MODERN SCIENCE, TAKING SPECIALLY INTO ACCOUNT THAT NO ONE KNOWS WHAT IT MEANS.

Bertrand Russell

CARNOT'S PRINCIPLE IS THE MISSING LINK BETWEEN LORD SNOW'S TWO CULTURES.

Louis Tibal-Duclaux

NO FORM OF ENERGY IS SO DANGEROUS, SO POLLUTING, SO COSTLY AS ... NO ENERGY AT ALL!

Louis Timbal-Duclaux

CLOSING SUMMARY

Paul Black
Chelsea College, London

I want to say something about where we are, then to propose a few conclusions about which way we can now go, and finally to offer some remarks to guide us on our journey.

First, about where we are. In the spirit of this conference, we can think of ourselves sat on time's arrow. We have come from the past, the home and source of our physics, and of our traditional ways of teaching. We have learnt here that physics was done by real people not by Gods. So it helps to see that Maxwell was human, refusing to read Botzmann's paper because it was 72 pages long and contained 69 equations, and that Clausius, in a family of eighteen children, might have been expected to invent a statistical approach!

But also our past can get things wrong for us. It isn't satisfactory, for example, to say that energy is the "capacity to do work". Three equal masses of an ideal gas, all at room temperature, but at pressures respectively above, at and below atmospheric pressure, all have the same energy: they don't all have the same capacity to do work. And many authors and teachers confuse the general claim of the Principal of Conservation of Energy with the much more limited statement that the First Law of Thermodynamics makes, where correct interpretation of

$$dU = \delta Q + \delta W$$

depends on careful understanding of the difference between the symbols "d" and "δ".

But now, in the present we can see more. The range of issues raised in this meeting has underlined the fundamental importance of the subject. The creation and death of the universe, information theory, self-regulating systems, all chemical reactions, changes in biological systems, new ways of thinking about ecology or about economics, optimisation of energetic systems in engineering, the world energy crisis - all of these require the same fundamental theory. For each and every one the slogan is the same "Change and Chance Rules All". So we are happy to be rich in ideas, although if this makes us want to give more to our pupils it can be a dangerous joy.

Figure 1.
The Story of Teaching - New Delight of Teacher - New Pain for Pupil.

If we think of moving to our future, what can we see for these pupils? A child who is 5 years old today will be 67 in the year 2050. What will have happened during that person's life? Will the world energy shortage have produced drastic changes in everybody's way of life? How will the explosion of information and communication have changed our ways of thinking about knowing and learning things. We don't know, but experience teaches us that:-

Monday's crazy idea
Is Tuesday's new theory
Starts Wednesday's technology
Becomes Thursday's daily life
And Friday's social problem.
(Next week perhaps -
It will appear in the textbooks!)

If there is one general lesson here it is this - that we can't prepare for the future by studying only today's problems.

So, from the picture of where we are, we can begin to think of which way we can now go. But what we do in this part of physics in schools depends partly on what we think of the aims in schools in general. For example, many of us were brought up in schools where the school title could well have been:-

School to Teach Dead Physics

The subjects on our timetables were the traditional topics - Sound, Heat, Light, Mechanics, Electricity and so on. The motto of these schools was clear:-

All Physics Old and Approved by the Authorities

Now many teachers try to change this - but there are different ways to change. One way that has many supporters gives a new name to the schools:-

School to Strengthen Pupils' Existing Culture

To achieve this aim, the subjects must now be quite different, based on pupils' experience we have Kitchen Physics, Garage Physics, T.V. Physics, Home Heating Physics. The motto of these schools states an important underlying principle. It says:-

We Answer Pupils' Questions. We Don't Ask Any.

I don't think the spirit of this meeting has supported either of these types of school. Although the second-type is doing something important, it is also missing something of great value. So we want a third type of school, the notice-board of which proclaims:-

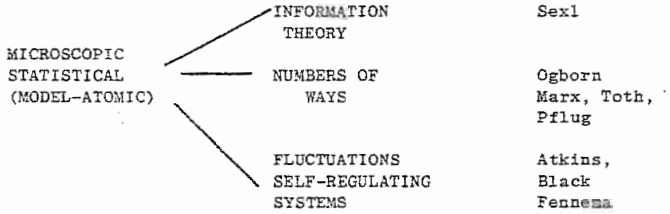
School to Enrich the Culture of Man

This is a more ambitious school. Its subjects are The Universe, Life, Creation, Entropy. And its motto reflects the same ambition:-

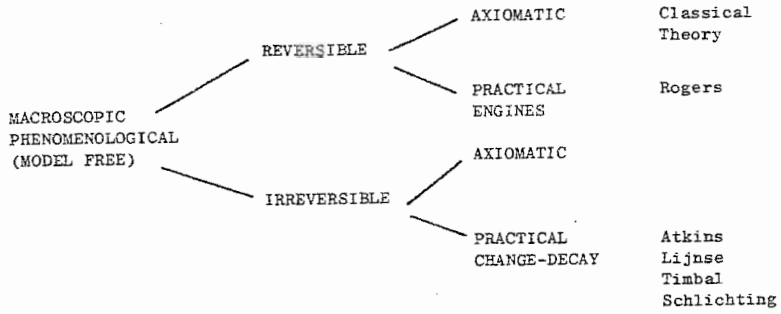
We Teach You Things You Did Not Know Already

Unless we are interested in this third school much of the discussion will be irrelevant to us.

However, the meeting has left us with a choice of ways to proceed in rethinking our teaching. The pattern that seems to me to have emerged can be summed up in the following way. There are two main lines of approach. The first is the microscopic and statistical approach, based on an atomic model of matter. Various aspects can be emphasised as follows, linked to the authors of relevant papers at this meeting:-



The opposite approach, based on a macroscopic and therefore phenomenological approach, has received attention from fewer of our speakers here. However, its main aspects can be set out as follows:-



We can choose to base teaching on one or on a mixture of these approaches. They can all be correct - but they differ from one another either in solving different problems or by solving the same problems in different ways.

I think we should listen particularly to scientists who are trying to form new approaches in applications of thermodynamics, in engineering, ecology and in global approaches to the world's energy problems which include considerations of fuel, food supply and materials supply within the same overall framework (1,2,3,4). They now use one or other of the related concepts of Free Energy, Available Energy, Useful Energy or Exergy. The latter, for example, is defined by:-

$$E = T_o (S_{Total}^{equilibrium} - S_{Total})$$
$$= U + p_o V - T_o S - \sum_i \mu_{i_o} N_i$$

where p_o, T_o, μ_{i_o} refer to the surroundings. This function clearly refers a situation to its environment: it would give a different value for E for a block of ice, for example, if it were at the South Pole, where it would be useless, to the value it would have in the Sahara desert, where it could be used to drive an engine.

To think of "energy" in this way is to give the word energy a new meaning, but perhaps one closer to the meaning it carries in everyday conversation. One way in which this idea could be carried out in practice is suggested in the following scheme. This is only a first speculation - an outline to start thinking of new ways to teach energy to pupils in secondary schools.

To start with, talk of the First Law of Thermodynamics is abandoned altogether. We start to talk of energy in a more general diffuse way. Headings are set out in Table 1.

Table 1 - A First Sketch of a Scheme for Teaching Energy

No First Law

Energy - See, Discuss Many Forms
Variety and Transformations

Do Some Sums - learn about Joules

Calculations on Everyday Things - Food, Fuels

Useful Things Energy Can Do

Sometimes Get all the Energy Out)
Sometimes Have to Waste Some) Study by Examples - this is how it is

Connection of "Waste" examples with Heat

So now two ideas of energy

Useful Energy	Book-Keeping Energy
Heat Flow	Heat and Work
Engines	Law of Book-keeping
Law of Spreading	

Why Are They Different?

Chance and Numbers of Ways

The main strategy is to build up a range of ideas about energy from many examples and calculations, without strict definitions. Then the examples studied are chosen to focus on degradation and non-availability atthe same time as bringing out that the right calculations can always "account for" the energy. At this point we deliberately, even dramatically,

split, emphasising to pupils that there are two kinds, Useful Energy and Available Energy. After this we can develop the two themes separately : for the more able perhaps, and at a later stage, we may be able to return to work on their relationship through ideas of numbers of ways in a microscopic approach.

But this makes clear that our conference cannot remain inside its terms of reference. We must think again about the whole topic of the teaching of energy. Perhaps Figure 2 is the story of this conference.

WHAT WILL YOU LEARN?
I KNEW HOW TO TEACH ENERGY. NOW I GO TO LEARN TO TEACH ENTROPY
DID YOU LEARN HOW TO TEACH ENTROPY?
NO! AND - NOW I DON'T KNOW HOW TO TEACH ENERGY EITHER
HOME!

Figure 2.
Before and After - The Story of Lake Balaton

Finally we must be clear that what we are arguing about at the moment is only the beginning of an argument about the design of teaching. It is essential, given we can reach a clear understanding of the concepts involved and of the variety of ways in which they could possibly be approached or interrelated, that we appreciate that there is still a different and more difficult problem :that is to select from this a strategy, and then invent the tactics, for meeting the needs of pupils. Figure 3 which comes at the end of this text, gives my message about this problem. It's the way I want to end this summary - and so it's the way in which I want this conference to end.

But before doing that, it should be emphasised that if we want to see new and exciting ways of overcoming old difficulties in learning, we have to dig deeply into the fundamentals of the theory of the subject. I have a dream in which I am lost in a Budapest street and meet George Marx. When I ask him "Where am I?" he produces a graph of the temperature of the universe against its age - starting with 10^{30} K at 10^{-40} s. He points to a few K of temperature at about 10^{10} years and says "That is

where you are". George Marx always tackles a problem in a fundamental way, and in applying his approach to construct this conference he has served us all wonderfully well. So our thanks are due first to him. But I should also thank the many others who have helped. In particular we are grateful to Dr. Laszlo Kovács, President of the Educational Board of the Hungarian Physical Society, who has done so much to organise many events for the participants. Three others have also worked hard, quietly and efficiently to make this meeting go smoothly and comfortably for all of us. To Piroska Laczkó, our Conference Secretary, Eva Orosz, the Conference Assistant, and Magda Holczer, Secretary of the Hungarian Physical Society, I express special and heartfelt thanks from all participants.

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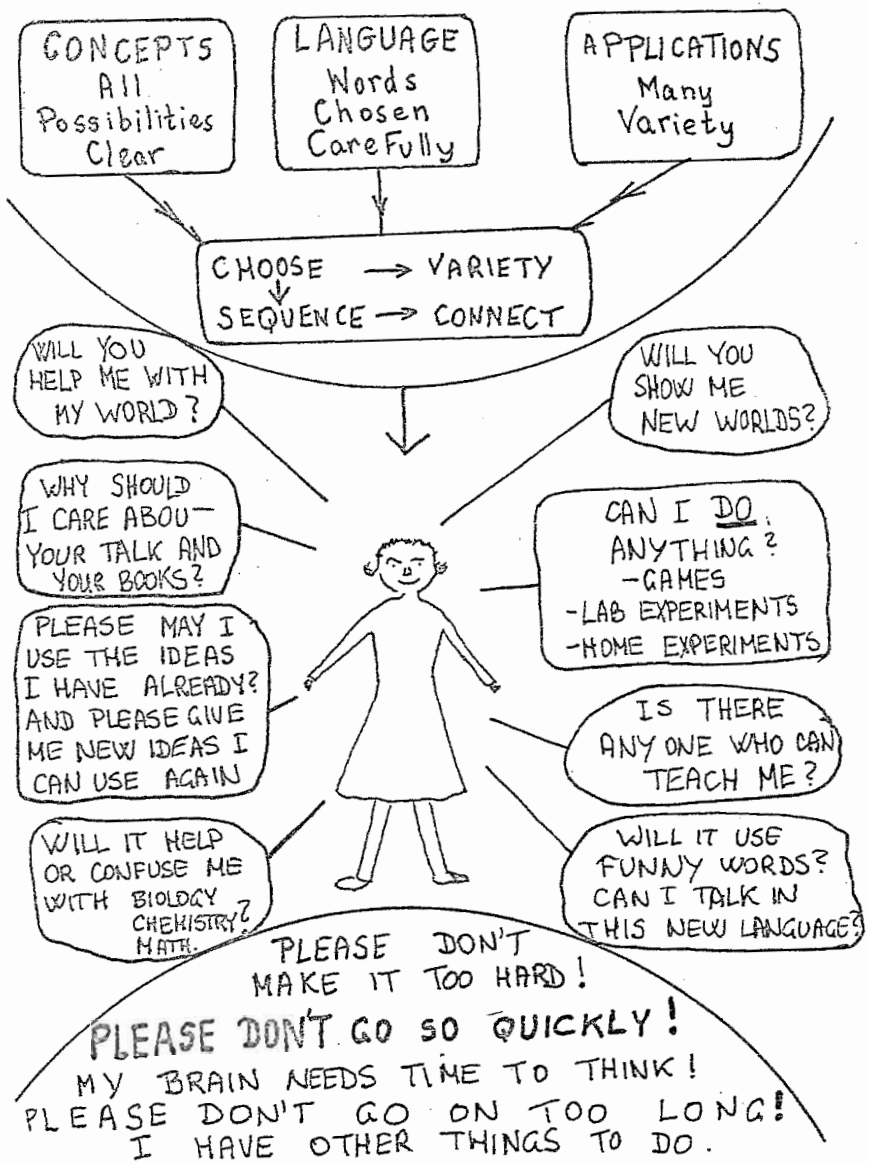
CONCEPTS All Possibilities Clear
LANGUAGE Words Chosen CareFully
APPLICATIONS Many Variety
CHOOSE → VARIETY
SEQUENCE → CONNECT
WILL YOU HELP ME WITH MY WORLD?
WILL YOU SHOW ME NEW WORLDS?
WHY SHOULD I CARE ABOU— YOUR TALK AND YOUR BOOKS?
CAN I DO ANYTHING? -GAMES -LAB EXPERIMENTS -HOME EXPERIMENTS
PLEASE MAY I USE THE IDEAS I HAVE ALREADY? AND PLEASE GIVE ME NEW IDEAS I CAN USE AGAIN
IS THERE ANY ONE WHO CAN TEACH ME?
WILL IT HELP OR CONFUSE ME WITH BIOLOGY CHEMISTRY? MATH.
WILL IT USE FUNNY WORDS? CAN I TALK IN THIS NEW LANGUAGE?
PLEASE DON'T MAKE IT TOO HARD!
PLEASE DON'T GO SO QUICKLY!
MY BRAIN NEEDS TIME TO THINK!
PLEASE DON'T GO ON TOO LONG!
I HAVE OTHER THINGS TO DO.

Figure 3. Teaching - Our Ideas meet the Pupils' Needs and the Pupils' Questions

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Das Leben strömt voll Energie.

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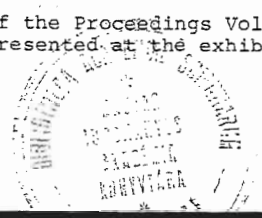
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